2014

Modeling of Water Quality in Canard River Watershed

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By

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A Thesis

Submitted to the Faculty of Graduate Studies
through the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2014

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ABSTRACT

Anthropogenic activities have disturbed the naturally sustained cycles beyond their self-recovering capabilities. Deteriorating surface water in Great Lakes has become a serious issue. To improve the water quality, the enhanced understanding of processes and sources of pollution is required. In this study, SWAT is used for modeling hydrological and pollutant fate and transport processes in agricultural dominated tile drained Canard River Watershed located in Essex County. SWAT model was developed with primary focus on understanding trends and sources of sediments and indicator microbe *E. coli*. Daily monitored weather and streamflow from 1995 to 2012 was used to calibrate and validate the model. The daily NSE for calibration period (2001-2007) and validation period (2009-2012) was 50% and 55% respectively. Sediments concentration and loading was found to be higher during winter and spring while lower in fall and summer. *E. coli* loading was higher during winter and lowest during summer.

ACKNOWLEDGEMENTS

The successful completion of this research project would not have been possible without the generous support of several people. I would like to take this occasion to thank my graduate advisor, Dr. Tirupati Bolisetti, who not only provided sound technical guidance and practical help, but was always full of encouragement. I am also very thankful for his invaluable assistance towards my professional career.

My very special thanks go to Dr. Rajesh Seth for facilitating my research, scientific guidance and for providing any possible support that a graduate student could need. I also acknowledge his valuable insights at appropriate times which directed the course of my research. I would also like to offer my sincere thanks to Dr. Nihar Biswas and Dr. Amir Fartaj for their suggestions with regard to this thesis.

I wish to thank Md. Masihur Rahman for his help with data acquisition, model set up and numerous discussions. I express my sincere gratitude to Carina (Xue) Luo for her help in getting GIS data. Without your help, this onerous task would not have been possible. I would also like to thank my friend Numanul Subhani for constantly encouraging me and motivating me towards my goal.

Finally, I would like to thank my family for their patience and precious support.

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LIST OF ABBREVIATIONS/SYMBOLS

AGNPS	Agricultural Non-Point Source
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
AOC	Area of Concern
BMPs	Best Management Practices
BWQM	Bacterial Water Quality Model
CANSIS	Canadian Soil Information System
CFOs	Confined Feeding Operations
CFU	Coliform Forming Units
COA	Canada-Ontario Agreement
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management Systems
DEM	Digital Elevation Model
DFO	Federal Department of Fisheries and Oceans
E. coli	Escherichia coli
EPIC	Erosion Productivity Impact Calculator
ERCA	Essex Region Conservation Authority
FEFLOW	Finite element sub-surface flow and transport simulation system
FORTRAN	Formula Translating System
GAWSER	Guelph All Weather Storm Event Runoff Model
GIS	Geographic Information System
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
GLUE	Generalized Likelihood Uncertainty Estimation
GLWQA	Great Lakes Water Quality Agreement
GRASS	Geographic Resources Analysis Support System
GSFLOW	Coupled ground-water and surface-water flow model
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
HRU	Hydrologic Response Unit
HSPF	Hydrologic Simulation Program Fortran
HydroGeo Sphere	3-D Physical Finite Element Model
IJC	International Joint Commission
ILOs	Intensive Livestock Operations
InHM	3-D Physical Finite Element Model
LIO	Land Information Ontario
LSPC	Loading Simulation Program in C++
Masl	Meters Above Sea Level
MCMC	Markov Chain Monte Carlo
Mike SHE	The European Hydrological System Model
MNR	Ontario Ministry of Natural Resources
MODFLOW	Modular finite difference ground-water flow model
MOE	Ontario Ministry of the Environment
MWASTE	Event Based Compartmental Model

NSE	Nash-Sutcliffe Efficiency
OGDE	Ontario Geospatial Data Exchange
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
ParaSol	Parameter Solution
PRMS	Precipitation Runoff Modeling System
PSO	Particle Swarm Optimization
QUAL2E	Enhanced Stream Water Quality Model
QUALHYMO	Surface Water Model
SCS	Soil Conservation Service
SSQR	Sum of squares of the difference
SUFI	Sequential Uncertainty Fitting
SWAT	Soil Water Assessment Tool
SWMM	Storm Water Management Model
SWRRB	Simulator for Water Resources in Rural Basins
USDA	United States Department of Agriculture
US EPA	United States Environmental Protection Agency
UV	Ultra Violet
WAM	Watershed Assessment Model
WARMF	Watershed Analysis Risk Management Framework
WMS	Watershed Modeling System

CHAPTER 1

INTRODUCTION

1.1 Background

In the recent years, human activities have significantly deteriorated environment. Over exploitation and unsustainable practices resulted in degradation of natural environment and resource depletion. Rapid industrialization, urbanization and intensive farming not only resulted in soil, air and water pollution; but also created global problems like ozone depletion, climate change, and global warming. Degradation of water resources has emerged as one of the most daunting challenges faced by most nations of the world. In this era, water is considered as most valuable resource. It finds its application in almost all spheres of human life. Impairment of water bodies across the globe rendered surface water unfit for drinking, domestic, agriculture, fishing, and industrial purposes. Moreover, it hampered the survival of aquatic flora and fauna along with deteriorating the aesthetic aspects of environment.

The Great Lakes constitute the largest fresh water system in North America comprised of five main lakes interconnected by series of rivers, waterfall and small lakes. They are spread across the US-Canada border and contain 84% of North America's fresh surface water, which is about 21% of world's fresh water supply (Schulte, 2013 and US EPA Great Lakes, 2012). Europeans arrived in this region in 1700s and settled along the coast of lakes and rivers. Since then these water bodies were used extensively for shipping, trading, drinking, industrialization, recreation and US-Canada border (Green et. al., 2010). International Joint Commission (IJC) was created by US and Canada in 1909 for regulating major issues pertinent to the great lakes like; water use, drinking water, shipping, hydroelectricity, agriculture, industry, fishing, recreation and shoreline property (IJC, 2013). Great Lakes Water Quality Agreement (GLWQA) was signed in 1972 between these two nations, binding them to control pollution and cleaning up industrial and communities' waste water being released into water bodies. Canadian federal government signed Canada-Ontario Agreement (COA) with Ontario provincial government to restore, protect and conserve the Great Lakes Basin Ecosystem. Detroit River was designated as Great Lakes Area of Concern (AOC) in 1987 due to contaminated sediments, fish consumption advisories, combined sewer outflows, and loss of wildlife and fish habitat (Green et. al., 2010).

Essex County has 23 sub-watersheds that drain water into Lake Erie, Lake St. Clair and Detroit River. This region is regulated by Essex Region Conservation Authority (ERCA) which was established in 1973 to restore and conserve county's original character. ERCA manages this region on watershed basis (ERCA, n.d.). The major challenges confronted by ERCA include drinking water quality, bacterial beach contamination, algal blooms and eutrophication, in-stream and lake low dissolved oxygen, loss of fish and wildlife habitat, recreation and tourism, fishing, etc. To understand the water quality conditions better, ERCA initiated several regional surface water monitoring programs including 36 in-stream and 28 near shore monitoring stations, flow monitoring at certain locations and wet/regular weather sampling. It also started four pilot watershed monitoring studies in Belle River, Little River, Canard River and Big Creek watersheds (Bejankiwar, 2010).

Watershed is a geographical area that drains its precipitation into single river or lake. As a single watershed may be spread across different municipal boundaries, thus regulatory decision impacting a particular watershed should involve the consent from concerned administrative authorities. Watershed may have different landuse patterns, different soil types, and different management operations and practices which affect the hydrological processes. In order to manage the watershed properly better understanding of these local conditions and processes is utmost important.

The hydrological cycle starts with precipitation chiefly in the form of rain or snow. After precipitation, water infiltrates into soil enriching water table and also percolate deeper to enrich deep aquifers. The water in vadose zone is withdrawn by roots and released back to atmosphere by evapotranspiration from the stomata openings in leaves. When soil is saturated, the excess water gets stored in depressions. After filling the depressions, the water start flowing on the surface of earth along the slope in the form of sheet and known as sheet flow or surface runoff. It keeps on flowing on the surface until it reaches nearby reach or stream and starts flowing in stream known as streamflow. As the friction in stream is less as compared to surface, the velocity of water in stream is higher. This streamflow reaches rivers and lakes. But during its flow on land surface, sediments and various chemicals like petrol, fertilizers, paints, metal particles, pesticides, insecticides, nutrients like phosphorus and nitrogen, and microbial contaminants get washed away and reach water bodies making water unfit for aquatic life as well as for human use.

Water balance analysis provides knowledge about the amount of water available in form of surface water or ground water for a watershed; as well as its inflows and out flows. It categorizes total water entering the watershed in the form of precipitation or artificial inflow and its egression in the form of surface runoff, evapotranspiration, baseflow or removal for human consumption. This analysis helps in better estimation of available water for its effective management and utilization. It also helps in determining the appropriate land use management practices and techniques for enhancing the water quality. The impact of change in land use pattern on water budget should also be considered before implementation.

Water quality is impacted by sediments, nutrients, chemicals and pathogens washed off by water flowing on land surface. These loadings can be estimated based upon the particular characteristics of watershed. Loadings can be categorized in two types i.e. point and non-point source loadings. Point source loading arises from single identifiable source that enter the stream at one point like sewage and industrial discharges; while non-point source loadings are those which originate from many diffuse sources spread over the space like runoff containing pesticides from agricultural area entering river. Point source loadings are almost constant throughout the year and mostly treated before discharging into streams. The discharge quality standards are set by regulatory authorities and they are monitored regularly to ensure safe water quality. The non-point sources lead to sudden surge in the pollution levels during precipitation and surface runoff events. Therefore estimating the effect of non-point sources on loading becomes significant for estimating the water quality and ensuring safety standards. It also becomes important to identifying the major contributing factors to develop strategies for reducing loading rates.

Maintaining and preserving water source quality has become top priority in the wake of recent disasters. As evident from Walkerton, Ontario accident in 2002, the contamination of drinking water with *E.coli* and *Campylobacter jejeuni* caused bloody diarrhea and gastrointestinal infections in more than 2300 people and death of seven persons (Dennis 2002). Detection of pathogens in water source alarmed the regulatory authorities to enforce stringent control measures and efficient source protection strategies for ensuring the health and safety of residents. Pathogens namely fecal coliform, protozoa and viruses are excreted by animals and humans. They can contaminate water by point or non-point sources. Point source contamination includes discharge of untreated sewage or combined sewer. Non-point sources of pathogens include spatially dispersed human, wild animals, pets, livestock and manure application on fields. Better source characterization is utmost important for identifying the significant contributor and for designing the control strategies. Best management practices for handling livestock and manure application need to be developed for prevention of potential surface and groundwater contamination.

Modeling complex processes governing the hydrology, sediment erosion, nutrients and pathogen pollution by using software model tools enabled the scientific community to understand, verify and implement the best management practices. These tools provide the opportunity to estimate loadings from contributing sources, forecasting and determining the impact of climate change on each parameter. Various models have been developed and find wide application based on their area of expertise. Soil Water Assessment Tool (SWAT) is one such tool which simulates the hydrological, sediment, nutrient, pesticide and bacterial processes on a continuous, daily basis. SWAT was developed by USDA Agricultural Research Service. It is suitable for simulating watersheds with predominant agricultural areas. It has been used extensively for performing water balance, nutrients and sediment analysis all across the globe. Recently incorporated bacterial fate and transport module has been explored by few researchers to analyze the pathogen loadings. Large spatial and temporal variability of microbial contamination and limited data availability limit the application of this particular aspect of SWAT.

This research is based on Canard River watershed located in Essex County. It is the largest watershed in this region that drains water in Detroit River. This study is focused on simulating the water balance based on observed meteorological and flow data. It also tried to determining the important parameters related to sediment loadings and correlate the simulated trends with limited observed data. Based on limited available data related to microbial sources, this study also performed the sensitivity analysis for detecting key factors influencing the microbial fate and transport which can be monitored and verified in future.

1.2 Problem Definition

The water budgeting process provides quantitative and qualitative analyses of water in a watershed. In Canard River Watershed water budget analysis could assist in addressing the potential issues related to impact of development, pumping rates from different sources and assessing the effect of different water use activities. The streams are fed by snow melt and runoff, but during summer they generally become dry posing significant stress. Significant area of watershed is under tile drainage, but its impact on local hydrology is not clearly understood. The quantitative analysis can put some light on these problems and help in better management of water. Essex Region Conservation Authority has found high concentration of *E. coli* in several grab samples collected over different regions indicating poor to worse water quality in this region. Higher *E. coli* concentration in near shore areas has led to closure of several beaches on Lake Shoreline. More over algal blooms in Lake Erie has also been attributed to higher nutrient loadings from draining areas. Sediments settled at river bed pose serious threats to ships passing through Detroit River and result in heavy dredging expenses (Green et. al. 2010). The water quality analysis can assist in understanding the key processes involved for abating these challenges. To counter these problems following objectives were defined:

1.3 Objectives

The major objectives of the study are

- To perform Water Balance
- To estimate Sediment Load
- To advance the current knowledge on microbial fate and transport processes in tile drained watershed by using GIS based ARC SWAT Model.
- To determine the major contributing sources for sediment and microbial loadings

1.4 Structure of Thesis

This thesis is composed of six chapters. First chapter provides introductory knowledge about this study followed by defining the problem statement and objectives to be achieved. Chapter two provides elaborated discussion on literature reviewed for understanding the processes involved in water quality modeling and different approaches for solving the problem. Chapter three provides insight on methodology and hydrological model setup for Canard River Watershed. Sensitivity analysis, calibration and validation of model are discussed in chapter four. Various findings about water budget, sediment and microbial processes are discussed in chapter five. Conclusion and recommendations of this study are presented in chapter six followed by references and appendices.

CHAPTER 2

LITERATURE REVIEW

The literature was reviewed for understanding the mechanisms regulating the hydrology and contaminant fate and transport within the watershed. This section discusses the underlying conceptual framework which guided this study. A comprehensive review has been provided on different processes governing hydrology, sediment, nutrients, and microbial sources, persistence and transport on surface, in soil and in stream. It is followed by different modeling approaches used to simulate these processes.

2.1 Water Budget

Water budget is a process of quantifying various components of hydrological cycle within a watershed. It involves analysis of quantities of water inflows, outflows, uses and storage within a particular geographic area due to natural and anthropogenic activities. Effective water management and formulation of land use development strategies are based on sound water budget. In Ontario, water budgeting is considered an essential step to support decision making in water management activities namely, source protection planning, water permitting, low water response, sub-watershed and watershed planning, environmental impact assessment and dam/reservoir management.

There are several Ontario legislations related to water budget which are combined under The Living Water Policy Project, 2010, E-Laws Ontario, 2010 (AquaResource, 2013). Key legislations are presented in Table 2.1.

Table 2. 1: Ontario legislations related to water budget (AquaResource 2013)

Regulatory Authority	Legislation	Water Budget Application
Ontario Ministry of the Environment (MOE)	Clean Water Act, 2006, S.O. 2006, c. 22	• Identify potentially hydrologically stresses sub-watersheds • Identify municipal water supplies that may not be able to meet current or planned future water demands
	Environmental Assessment Act, 1976, 1997	• To determine the hydrologic, hydrogeologic and ecologic impact of a proposed project
	Environmental Bill of Rights, 1993, S.O. 1993, c. 28	• To identify applications for permits to take water and other items that may be relevant to water budgets
	Ontario Water Resources Act, R.S.O. 1990, c. O.40	• To develop strategies for managing water takings • Required in other areas like wastewater assimilation
	Safeguarding and Sustaining Ontario's Water Act, 2007	• To report water use information for regulatory commitments on the local, watershed, and Great Lakes scale
	Water Opportunities Act, 2010	• For assessment of sustainable development and conservation planning
Ontario Ministry of Natural Resources (MNR)	Aggregate Resources Act, R.S.O., 1990, c. A.8	• To estimate possible impacts of pits or quarries on groundwater and surface water resources, and mitigation • To analyze pre and post development hydrologic and hydrogeologic conditions for the rehabilitation of the aggregate extraction site
	Conservation Authorities Act, R.S.O. 1990, c. C.27	• For flood control, reservoir management and sub-watershed planning
	Lakes and Rivers Improvement Act, R.S.O. 1990, c. L.3	• To estimate hydrologic parameters like streamflow, reservoir storage, outflow required for designing and analysis of dams
Federal Department of Fisheries and Oceans (DFO)	Fisheries Act, R.S., 1985, c. F-14	• To estimate in-stream flows and other hydrological impacts that may influence aquatic health
Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA)	Nutrient Management Act, 2002, 2009	• To develop agricultural land management practices

2.2 Hydrological Cycle

The accurate estimation and understanding the dynamics of hydrological cycle components are mandatory in order to address the above legislations. The hydrological cycle can be studied on different spatial (Watershed, Sub-watershed, Catchment) and/or temporal scales (Seasonal, Annual, Long term). The most important components include precipitation, interception storage, depression storage, infiltration, surface runoff, evapotranspiration, unsaturated flow, shallow and deep aquifer recharge, snow melt, baseflow, and streamflow as shown in Figure 2.1.

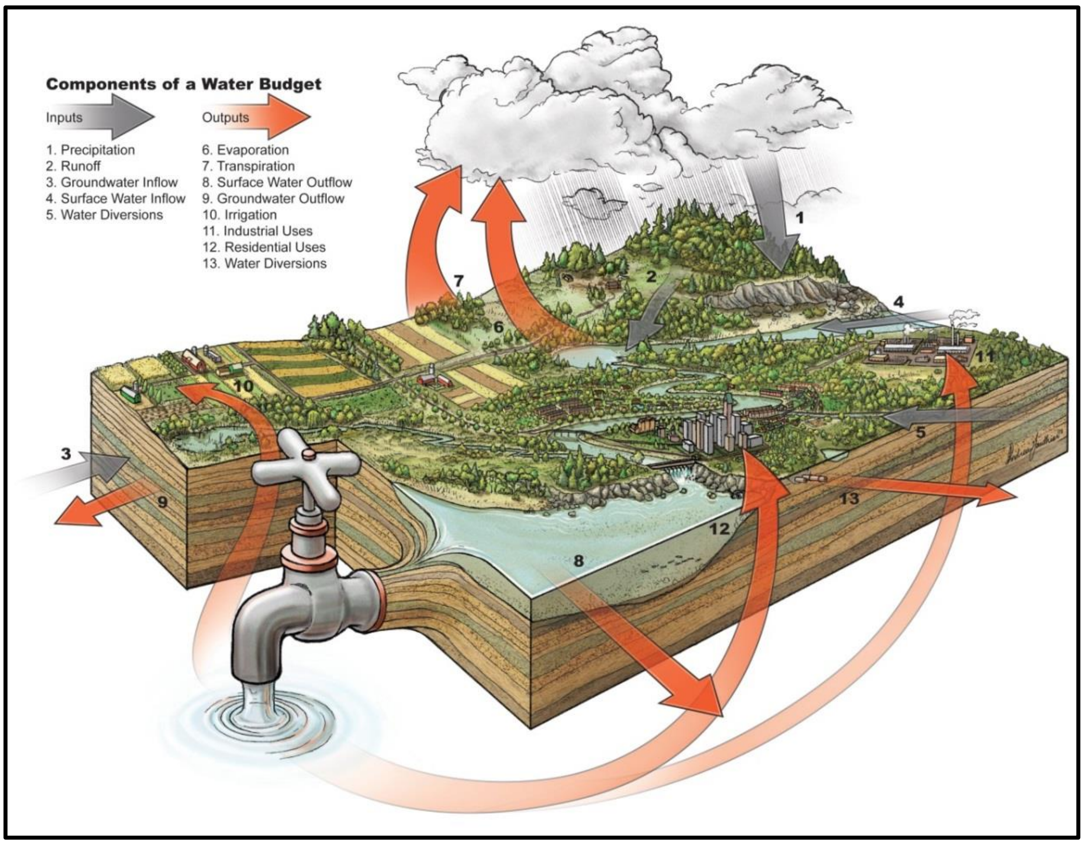

Figure 2. 1: Components of a Water Budget (Conservation Ontario 2009)

All components of water balance can be expressed by equation 2.1:

$$P = RO + AET + I + D + A \pm \Delta l \pm \Delta s \pm \Delta g \qquad \text{Equation 2.1}$$

where;

P = Precipitation

RO = Surface runoff

AET = Actual evapotranspiration

I = Interflow

D = Groundwater discharge

A = Anthropogenic inputs (septic systems) and/or supplies/abstractions

Δl = Change in land surface storage

Δs = Change in soil moisture storage

Δg = Change in groundwater storage

2.3 Water Pollution

Water carries various pollutants while flowing on the land surface, passing through soil-pores and migrating through tiles. Pollutant particles gets dissolved in water or carried as suspended particulate matter. It can be of organic or inorganic nature. It can also be classified as natural or artificial. Weathering of rocks, soil erosion, dissolution of various minerals etc. are natural processes but it's the human introduced artificial chemicals, different land use and management practices, that led to change in natural settings and disturbed the pristine natural healing ability of nature. The main pollutants that are under the radar of conservation authorities include sediments, plant nutrients, toxic chemicals, pesticides, fertilizers, and pathogenic strains of bacteria, protozoa and viruses. They are posing severe environmental and health challenges thus demand keen attention and quick response.

2.3.1 Sediments

Sediments are the soil particles that are formed from weathering of rocks by wind, rain, snow, plants, animals, or human activities. These particles vary greatly in size from few microns to millimeters in diameter. They are generally divided into three categories based on size and properties, sand (largest particles that settle quickly), silt (intermediate sized particles) and clay (smallest, negatively charged particles that don’t settle quickly in fresh water). Sediments are eroded on land surface by sheet, rill or gully erosion while in river they are eroded from stream bed or banks. Erosion depends upon intensity of rainfall, vegetation cover, season, land use and management, soil type, and slope. Agricultural activities like tillage, ploughing, and fallow land as well as deforestation hastens soil erosion. In streams, the sediments get eroded from bank and bed during high streamflow intensity.

Sediment loss from agriculture areas reduces soils fertility. They deposit in rivers and reservoirs clogging beds and reduce percolation. Moreover deposition reduces carrying capacity of river by reducing channel depth, which hinders navigation as well. River and lake dredging incurs additional costs. Enhanced turbidity reduces sunlight penetration in river water that promotes pathogen growth and limit available energy for aquatic autotrophs. This hinders aquatic life survival and habitat. Sediments also act as carrier for other pollutants. Different chemicals and pathogens stick to sediments and are transported, buried and resuspended along with them in rivers and lakes. They also harbor and thrives pathogens in rivers beds, which gets suspended by vigorous churning during storm events and infect population consuming that water.

2.3.2 Nutrients

Nutrients are essential elements that are required for plant growth. They enter water bodies along with sediments or as dissolved solids during agricultural runoff or baseflow. Limited amount of nutrients in streams is required for healthy aquatic life, but excess of these nutrients result in algal blooms. Algal blooms consume most nutrients and dissolved oxygen and limit their supply for other aquatic life forms. The decaying algae also excavate more oxygen leaving the water bodies unfit for aquatic flora and fauna. Among all nutrients phosphorus has been found to be rate limiting due to it less availability. Thus more focus is concentrated on its control.

The nutrient loads generally occur from agricultural runoff similar to sediment loadings. But tile flow also contributes significantly to this loading in heavily tile drained watersheds. These loadings can be minimized by adapting Best Management Practices (BMPs). These practices provide practical, affordable solutions to reduce loading without affecting farm productivity. Commonly implemented BMP's include, soil, water, irrigation, manure and integrated pest management also others like no till, buffer strip, stream side grazing, cropland drainage, etc. (OMAFRA – Best management Practices, 2014). Service Ontario provides guidelines, manuals and assists farmers to implement BMPs.

2.3.3 Pathogens

Microbes are present everywhere on earth; in water, soil, air and even within animal bodies. Some microbes are beneficial for humans, but some are extremely dangerous for human health. These harmful microbes are called pathogens, which if enter human body through air, water or food cause severe illness, allergies, and death. Water contamination by pathogens and impairment of water bodies raised critical water quality issues across the globe. Pathogens are the leading cause of impairments in rivers and streams in USA, contaminating 29% of impaired streams (USEPA, 2009). It prompted to determine the sources, understand the survival, and transport processes of pathogens in different environmental conditions.

2.3.3.1 Source

Various microbial species (bacteria, protozoa, fungi, virus, and algae) are considered as pathogens. Among all pathogens the most frequently water polluting agents (Fecal coliforms and *E. coli*) originate from fecal matter of human, animals and birds. It is difficult and expensive to determine the concentration of all pathogens in diverse environmental settings. Fecal coliform reside in warm blooded mammalian intestine and do not survive in nature for long duration under normal circumstances, thus their presence in surface or ground water is clear indication of fecal contamination. *E. coli* is subset of fecal coliform whereas fecal coliforms belong to total coliform bacteria (Smith, 2000). Among all fecal coliforms, *E. coli* was selected and designated as indicator bacteria (USEPA, 1999).

Most common sources include untreated sewage disposal, leakage from faulty septic tanks, pets, livestock (cattle, horse, and pigs), wildlife (Deer, raccoon, opossum, striped skunk, coyote, badger, bobcat, red fox, gray fox, swift fox, beaver, mink, muskrat, river otter, spotted skunk, weasel, armadillo, woodchuck, and porcupine) and birds (turkey, ducks, geese) (Parajuli, et.al., 2009).

Municipal waste is point source of pathogens while septic tanks, manure application on fields, wildlife, livestock grazing, and migratory birds constitute non-point sources. Municipal waste water treatment plants generally treat sewage and disinfect it before discharging to meet regulatory standards. According to MOE regulations, the *E. coli* monthly geometric mean density in treated sewage waste water should not exceed 200 cfu/100 ml (Pileggi, 2008). Waste water from faulty septic tanks leaks to underground water or to nearby drainage network infecting them with pathogens and resulting in concentrations higher than regulatory standards. The microbes present in pets' and other animals' feces in urban areas directly enters stream during runoff event, as most of the water enters storm sewer in urban settings that discharge directly into stream or lake.

Livestock (beef cattle, swine, horses, sheep, turkey, chicken, ducks, goat, rabbit and lamas) are reared in feedlots or on open pastures. Microbial contamination form grazing operations are spread across the pasture. Stream also receives direct microbial loadings from animals, when they come in direct contact with stream for drinking or wallowing. Feces generated from intensive livestock operations (ILOs) or confined feeding operations (CFOs) are generally stored at site and later spread on fields in the form of manure. The microbial concentration in manure increases or decreases based on moisture condition, temperature and exposure to solar radiation.

Wild animals and birds dwell in forest, urban and agricultural areas. They also constitute non-point source microbial loadings. Some animals like beavers, muskrats, waterfowls, Canada geese, ducks, etc., that inhabit near streams contribute towards microbial loading more than other animals living on land areas. Migratory birds also have significant seasonal impact on wetlands and water bodies during their sojourn. There are several naturalized *E. coli* species which exist in soil. They also enter stream during baseflow and runoff events. It is difficult to determine the percentage of animal released and naturalized *E. coli* in water by normal tests.

2.3.3.2 Growth, Survival and Decay

Fecal coliform and *E. coli* proliferate inside the intestines of warm blooded animals but their ability to survive in manure, soil, groundwater, river and sediments is limited. Their survival depends on moisture, temperature, competition, natural predation, solar radiation, soil, pH, nutrient, and organic matter. But nutrient availability, temperature, competition, and predation seem to be the most influential factors governing pathogen survival in nature (Bition and Harvey, 1992 and Jamieson et. al., 2002). The growth follows zero order growth kinetics, while death follows first order decay kinetics.

Manure:

Kudva et. al. (1998) discovered that *E. coli* in ovine manure can survive under natural conditions for 21 months and its concentration ranged from 10^2 to 10^6 CFU/g prolonged periods in incubated manure without aeration but it was still lower than natural conditions. Van Kessel et. al. (2007) compared microbial concentration in cowpats under laboratory and field conditions and observed higher decay rate under shaded field conditions. Concentration of *E. coli* and fecal coliforms first increased and then declined afterwards.

Jiang et. al. (2002) tested the fate of *E. coli* O157:H7 in manure amended soil and survival ranged between 77 to 231 days. *E. coli* in non-autoclaved manure amended soil showed greater survival than autoclaved mixture. Manure to soil ratio, temperature, and competition from indigenous microbes were discovered to be contributing factors. Franz et. al. (2011) also checked *E. coli* O157 survival in manure amended soil from animal, food and human isolates. They found out the survival range varied from 47 to 266 days and isolates from human showed significantly prolonged survival (median 211 days) than animal isolates (median 70 days).

Himathongkham et. al. (1999) conducted a study to determine the time required under different temperatures to hold the manure before applying to field. The inactivation rate corresponded to first order reaction with decimal reduction times. Pathogens survived longest at 4 ℃ and survival time kept on decreasing at elevated temperature ranges. It was suggested to store the manure for 105 days at 4 ℃ while 45 days at 37 ℃ for achieving 10^5 fold reduction. Temperature, solid content, microbial content, pH, oxidation-reduction potential and time were found to influence the survival.

Soil:

After manure application, *E. coli* attach to soil particles and foliage preferentially. *E. coli* showed 3.9 times attachment preference to soil particles between diameter 16 – 30 µm. They also leach to lower soil layers, groundwater and tiles during rainfall event (Oliver et al., 2007 and Fenlon et. al., 2000). *E. coli* growth depends on moisture conditions of soil. At 57% moisture level, slight growth was observed, while at 25% microbes only persisted whereas at 4% they died (Gallagher et. al., 2012).

Brennan et. al. (2010) performed lysimeter tests and determined the persistence of *E. coli* in controlled conditions for more than nine years. They also discovered that autochthonous *E. coli* can become naturalized under low temperature conditions. Preferential flow was observed to be significant transport factor in soil.

E. coli growth and survival is directly correlated with organic content and temperature. Growth was observed at low temperatures while elevated temperatures prompted cell death. Lower organic concentrations resulted in decay, where higher organic content promoted survival even at elevated temperature (Melek, 2012). Sjogren (1994) concluded that *E. coli* can survive for extended period of 23.3 months under pH 6.8 – 8.3, 5 ℃ temperature and saturated moisture conditions. Jamieson et. al. (2002) also confirmed that most suitable pH value lies between 6 and 7.

E. coli concentration values higher than regulatory standards in groundwater and tile drained water were observed in several studies (VanderZaag et. al., 2010, Jamieson et. al., 2002 and Moreno, 2003). Common manure application on fields results in significant transfer of pathogens to sub-surface water during irrigation and precipitation event. It also provides suitable moisture conditions for microbial growth.

Protozoan grazing especially by amoeba significantly reduces *E. coli* in soil after manure application. Peak concentration reached 2 - 4 days after manure application, but abrupt decrease was observed following that period with simultaneous increase in amoeba concentration, reaching its peak after 7 days. It was attributed to the flexible shape of amoeba allowing it to enter into soil pores and feed on hidden bacteria (Enzingeri and Cooper, 1976).

Water:

Pathogens readily perish upon exposure to aquatic environment. Physiochemical factors (temperature, exposure to UV light, pH, heavy metals, and ion concentration), competition, bacteriophage, and flagellate predation in freshwater wreak havoc on their population (Sanders and Porter, 1986 and McCambridge and McMeekin, 1981).

Size selective preferential grazing behavior of micro flagellate towards *E. coli* was apparently the major factor in bactericidal activity. Bacteriophage effect was not that significant whereas indigenous micro flora and nutritional availability enhanced the survival rate of pathogens (Wcisło and Chróst, 2000). Salinity has deterrent effect on microbial survival (Anderson et. al., 2005). Temperature plays an important role in controlling microbial concentration but at lower temperature of 4 ℃ at the bottom of water body promote bacterial survival. Microbes can survive long winter in bed sediments (An et. al., 2002).

Pathogens tend to attach to sediments and settle down on bed along with sediments. As compared to water column, sediments provide safe harbour to pathogens. They survive for longer duration in sediments than in water (Craig et. al., 2004). Their concentrations vary broadly in sediments from different sources as well as at different locations within same water body (Pachepsky and Shelton, 2011). Under controlled conditions, replicated sediment samples showed higher variability as compared to water samples (Anderson et al., 2005). No correlation between concentration in sediment and water exist during baseflow. During storm event major contribution is from land loading (Pachepsky and Shelton, 2011). Coarse sediments do not provide enough protection from protozoan grazing but may contain more nutrients for supporting bacterial survival (Cinotto, 2005).

Clay particles provide more protection and enhance their survival (Roper and Marshall, 1974). Significant direct relation was confirmed between microbial concentration and silt and clay particles percentage in sediments (Atwill et. al., 2007). Proximity to source has also significant impact on pathogen concentration in sediment (Bergstein-Ben Dan and Keppel, 1992).

2.3.3.3 Transport

Pathogens from soil are carried to stream along with surface runoff during precipitation event. They also get transported to lower layers of soil, groundwater and tile drainage by migration along with percolating water. In stream they are carried further to longer distances. Temperature, soil type, sediment size and type, macropores in soil, manure, and solar radiation have been found to impact transport of pathogens in surface, ground water, tiles, and stream (Jamieson et. al., 2002).

Surface Transport:

Advective flow on overland surface is responsible for transporting pathogens to streams. They are transported as free suspended particles and attached to soil particles or manures. More fecal coliforms attach to clay and silt particles than sand. But with the application of manure microbial fraction attaching to clay and silt reduce significantly but fraction attaching to sand decreases only slightly (Guber et. al., 2007). Field scale study showed application of manure to different land uses (pasture, cultivated and mixed land use) did not affect *E. coli* loading to runoff significantly. But grazed sites were observed to have higher *E. coli* loading than cultivated sites (Harmel et. al., 2010).

Sub-surface Transport:

Significant microbial transport in intact soil occurs through macropores instead of soil capacity (Smith et. al., 1985). Negligible amount of microbes are present as free cells but mostly get attached to soil particles or agglomerate to form clumps (Reddy et al., 1981, Abu-Ashour et. al., 1998 and McDowell-Boyer et. al., 1986). They clog the soil pores while passing through them and form biofilms. Filtration is dominant in *E. coli* removal process when soil particle diameter is below 0.02 mm (Foppen and Schijven, 2006). But in freeze-fractured clay after several freeze thaw cycles, this filtration capability is reduced to some extent (Rosa et. al., 2010). During passage of *E. coli* through soil, they get adsorbed to soil. Soils having higher clay content have higher microbial adsorption capacity as compared to soils with lower clay content (Ling et. al., 2002).

Tile Drainage:

Pathogen transport to tile drainage system has been observed under all manure types and different application methods. Soil water content during manure application and precipitation within two to three weeks after application are most significant factors that contribute towards migration of pathogens into tiles. Manure application should be restricted when tiles are flowing (Jamieson et. al., 2002). Sub-surface manure application reduces the bacterial loss in surface runoff, but increase the contamination of tile flow and ground water (Crane et. al., 1983 and Warnemuende and Kanwar, 2000). Macropores developed by earthworm, insects, burrowing and cracking of clay soils during summer are responsible of majority of *E. coli* transfer (Jamieson et. al., 2002). Within the tile majority of microbes migrate as sediment attached particles instead of freely suspended particles.

Tile drainage has been observed to significantly contribute pathogen loadings to stream. Moreno (2002) observed 1.2 X 10^6 CFU/100ml peak concentration in tile drained water resulting from precipitation and irrigation. Fall (2011) also observed higher *E. coli* levels in streamflow when tile drainage was active indicating significant contribution of tile flow towards pathogen loading.

In-Stream Transport:

Stream receives microbial loadings from direct depositions, surface runoff, ground water and tile flow. Bacterial Water Quality Model (BWQM) developed for Salmon River watershed in British Columbia, Canada, predicted 70 – 80 % of fecal coliform loadings originated from snow melt surface runoff; while 20 – 30 % came from lateral flow (Zhu et. al., 2011). Within stream microbes are transported by advection, dispersion and sediment adsorbed suspension – resuspension processes (Jamieson et. al., 2004).

Bed stream sediments act as safe microbial reservoir, where they hide from predators, survive during harsh climate conditions, proliferate and re-enter in water column during sediment resuspension. Artificial flood experiments conducted in New Zealand revealed the occurrence of *E. coli* peak during rising limb of hydrograph. It was attributed to bed and bank sediment associated *E. coli* resuspension during turbulent rising limb as *E. coli* peak coincided with total suspended solids turbidity peak (Nagels et. al., 2002 and Muirhead et. al., 2004). This observation was further confirmed by Davis-Colley (2007), that early peak of *E. coli* during storm is due to sediment resuspension instead of contribution from surface runoff. Further (Cinotto, 2005) found that point sources do not contribute to rise in *E. coli* concentration during storm event. Bed sediments have limited supply of microbes as *E. coli* peak receded during the rising limb of storm hydrograph (Henson et. al., 2007 and Jamieson et. al., 2005b).

Higher *E. coli* concentrations were observed during two storm events after long drought, but not after third storm event in Southern California by Evanson and Ambrose (2006). It was concluded that *E. coli* was washed away during first two storm events and microbes didn't get enough time to regenerate during third event. Fecal coliform concentration increases in estuary during fresh water flow because microbes desorb from benthic sediments at reduced salinity (Erkenbrecher, 1981 and Roper et. al., 1974).

Free cell settling rate is very low 1.6 m/day (Cizek et. al., 2008), whereas sediment associated microbial settling is fast due to higher density of sediment particles (Gannon et al., 1983). For determining sediment associated microbial settling; estimate of microbes attached to sediments is required. Researchers have contrasting view about these attachment fractions (Pachepsky and Shelton, 2011). Schillinger and Gannon (1985), Atwill et al. (2007), Jamieson et al. (2005b), and Jeng et al. (2005) estimated 16%, 10%, 20 – 44%, and 20 – 30% of microbes attached to sediments respectively while Auer and Niehaus (1993) estimated 90% bacterial association with sediments. These contrasting results might have resulted from different enumeration techniques applied. Commonly used enumeration techniques include filtration, fractional filtration, and centrifugation also various other physical and chemical dispersion techniques have been applied to disassociate sediment attached microbes (Soupir et. al., 2008).

The effect of suspended solids concentration on microbial attachment percentage is not clear. But if majority of microbes attach to sediments, then turbidity can be correlated with their concentration as represented by equation 2.2. Various researchers observed strong and weak relationships between *E. coli* concentration and turbidity also with total suspended solids concentration. Linear dependence is most common assumption;

$$S = K_d\,C \qquad \text{Equation 2.2}$$

Where: S is Amount of microorganisms associated with solid particles, CFU/g, C is Concentration in runoff, CFU/g, and K_d is Partitioning coefficient

K_d is related to Clay content of sediments by equation 2.3 (Ling et. al., 2003 and Pachepsky et. al., 2006)

$$K_d = A * CLAY^B \qquad \text{Equation 2.3}$$

Where: CLAY is Percentage of clay particles < .002 mm in soil, A and B are Slope and the intercept of the regression in log-log coordinates

It's extremely difficult to divide resuspended sediment attached bacteria into free floating and sediment attached. Most of the resuspended particles exist in form of few large flocks (Pettibone et. al., 1996).

2.4 Model Description

Hydrological system is governed by a large number of processes within a watershed. It is impossible to consider and simulate every single process. The main focus of water budget analysis is to ascertain the amount of water entering the system should be equal the amount of water leaving the system in order to make sure that all processes are accounted in modeling. By using numerical models these processes can be simplified and the components of the hydrologic system at the watershed and sub-watershed scale can be quantified for making water management decisions.

2.4.1 Types of models

Empirical, numerical and analytical modeling approaches are commonly applied to simulate natural processes. Empirical models estimate output from observed input and output relationships instead of evaluating individual processes that regulate the overall system. A numerical model estimates approximate physical processes of complex system by solving governing equations. Analytical models calculate governing equations for simple homogeneous systems. In hydrology, where parameters vary spatially and temporally, the numerical modeling approaches are more suitable.

Lumped models and physically based models are frequently employed in performing water budget analysis. A lumped parameter model assumes that for large systems parameters average values could be used to represent processes. Lumped parameter models do not give priority to spatial position for estimating values for different processes. On the other hand, a physically based model considers spatial position and is based on fundamental physical principles. They require extensive observed data to determine the cause and effect relationship of system processes and behavior.

Due to complexity of hydrological processes at watershed level, three basic numerical modeling techniques are implemented.

Groundwater models: They are used to determine groundwater levels, recharge discharge pathways and groundwater-surface water interactions resulting from changes in climate, land use, groundwater takings, and groundwater and surface water body interactions. Groundwater numerical models are generally used to evaluate changes in the steady-state water budget.

Surface water models: Surface water models are used to estimate runoff, peak flows, evaporation, transpiration, and infiltration due to changes in climate, land use, surface water storage and removal, wetland modifications, storm water management and flow diversions. They are also used to predict flood lines, sediment loss due to erosion, and water quality based on assessed flows.

Integrated continuum models: In Integrated models, surface water and groundwater equation are assumed to be integral part of larger system and they are solved simultaneously but climate processes are simplified. The conjunctive models are mostly physically based models.

2.4.1 Model Selection

Model selection is based on type of water budget analysis requirement and dominant flow processes i.e. surface water or groundwater in study area. If groundwater discharge significantly impacts the streamflow, then the complex groundwater processes should be considered while modeling. On the other hand if surface runoff dominates the water flow in watershed then modeling should be focused on simulating complex surface water processes.

2.4.2 Current available models

Various researchers explored and compared different aspects of hydrological modeling. Main software tools include Object-Oriented Guelph All Weather Storm Event Runoff Model – GAWSER (Hinckley, 1996), Hydrologic Simulation Program Fortran - HSPF

(Bicknell, et. al. 2000), Storm Water Management Model - SWMM, (Donigian and Huber, 1991), Soil and Water Assessment Tool - SWAT (Arnold et. al., 1998, Arnold et. al., 2005, and Neitsch et. al., 2004), QUALHYMO (UserManual, 2009), Agricultural Non-Point Source - AGNPS (Finn et. al., 2003), Hydrologic Engineering Center – Hydrologic Modeling System - HEC-HMS (Scharffenberg and Fleming, 2010), Precipitation Runoff Modeling System - PRMS (Leavesley et. al., 1983), Watershed Modeling System - WMS (Dellman et. al., 2002), Areal Non-point Source Watershed Environment Response Simulation - ANSWERS (Dabral and Cohen, 2001), Modular finite difference ground-water flow model – MODFLOW (USEPA, 1993), Finite element sub-surface flow and transport simulation system – FEFLOW (DHI WASY, 2013), Mike SHE (DHI Software, 2007), InHM (Ebel et. al., 2007), HydroGeo Sphere (Brunner and Simmons, 2012), Coupled ground-water and surface-water flow model - GSFLOW (Markstrom et. al., 2008), Loading Simulation Program in C++ - LSPC, (Tetra Tech Inc. and USEPA, 2002), Watershed Assessment Model - WAM, (SWET, 2006), Watershed Analysis Risk Management Framework - WARMF (Chen et. al., 1999), MWASTE (Moore et. al., 1989), Coli (Walker et. al., 1990), a model developed by Dorner et. al. (2004a). Important modeling characteristics and capabilities of these models are compared below in Table 2.2.

Table 2. 2: Hydrological Model Comparison

Model	Type	Lumped parameter vs Physically Distributed	Sediment Routing	Pollutant Routing	Tile Drainage	Bacteria Routing
GAWSER	Surface Water	Lumped Physical Distributed	No	No	No	No
HSPF		Lumped	Yes	Yes	No	Yes
SWMM		Lumped	Yes	Yes	No	Yes
SWAT		Lumped Physical	Yes	Yes	Yes	Yes
QUALHYMO		Lumped	Yes	Yes	No	No
AGNPS		Physical Distributed	Yes	Yes	No	No
HEC-HMS		Physical	No	No	No	No
PRMS		Distributed	No	No	No	No
WMS		Process based	Yes	Yes	No	Yes
ANSWERS		Distributed	Yes	Yes	No	No
MODFLOW	Ground water	3-D Physical Finite Difference	No	No	Yes	No
FEFLOW		3-D Physical Finite Difference	Yes	Yes	Yes	No
MIKE SHE	Conjunctive	3-D Physical Finite Difference	Yes	Yes	Yes	Yes
InHM		3-D Physical Finite Difference	Yes	Yes	Yes	No
HydroGeo-Sphere		3-D Physical Finite Difference	Yes	Yes	Yes	Yes
GSFLOW		3-D Physical Finite Difference	Yes	Yes	Yes	Yes

Hydrological Simulation Program FORTRAN - HSPF was developed in the early 1960's as the Stanford Watershed Model and later in 1970's, water-quality processes were added. FORTRAN was incorporated in the late 1970's. Pre-processing and post-processing software, algorithm enhancements and use of the USGS WDM system were developed jointly by the USGS and EPA in 1980’s.

HSPF simulates the water quality on pervious and impervious land surfaces and in rivers and well-mixed water bodies. It uses continuous precipitation and other meteorological records to estimate streamflow hydrographs and model the contaminant concentrations. It simulates interception soil moisture, evapotraspiration, surface runoff, baseflow, interflow, snowmelt, depth of snowpack and its water content, ground-water recharge, temperature, pH, organic phosphorus, orthophosphate, ammonia, organic nitrogen, nitrite-nitrate, sediment transport & detachment also its routing based on size of particle, pesticides, conservatives, dissolved oxygen, biochemical oxygen demand, phytoplankton, zooplankton, fecal coliform, channel routing, reservoir routing and constituent routing. HSPF can simulate one or many unit areas discharges into one or more streams or reservoirs. Any time interval ranging from one minute to one day which divides equally into one day can be used and any period from a few minutes to hundreds of years can be modeled. It is mostly used to assess the effects of change in land use, point and nonpoint source treatment alternatives, flow diversions, reservoir operations (Bicknell et. al., 2001).

Loading Simulation Program in C++ (LSPC) is a process based model that can simulate hydrological, sediment, nutrient, pollutant, and bacteria transport processes on land, in the subsurface and streams (Tetra Tech Inc. and USEPA, 2002). But tile drainage module is not incorporated in LSPC. It also demands extensive data for calibration, and expertise knowledge and significant time for modeling (Shoemaker et. al., 2005).

SWMM model is widely applied in urban sewer networks for analyzing surface runoff and flow routing by simulating surface and groundwater, stream routing, pollutant and bacteria transport. Individual storm or long duration simulations can be performed (Donigian and Huber, 1991). WMS is a process based model which includes surface and groundwater, and nutrient and bacteria transport components. But it doesn't include tile drainage module (Dellman et. al., 2002).

SWAT is a process based model which predicts the impact of climate and land management practices on hydrology, sediment, nutrients and microbial transport in surface runoff, groundwater, tile flow and streamflow (Gassmann et. al., 2007 and Du et. al., 2005). It can simulate results on daily, monthly and annually basis but cannot be used for single storm event. SWAT has been used extensively to model water budget and non-point source pollution (Shoemaker et. al., 2005 and Parajuli et. al., 2007).

Agricultural Nonpoint Source (AGNPS) pollution model of watershed hydrology was developed by U.S. Department of Agriculture (USDA) for solving complex problem related to managing nonpoint sources of pollution primarily from agricultural areas. AGNPS simulates the behavior of runoff, sediment, and nutrient transport from watersheds but doesn't include equations for bacterial transport and tile drainage flow (Finn et. al., 2003).

HEC-HMS can be used independently or in conjugation with other models to determine water availability from precipitation runoff relationships. It is also used widely for urban drainage, flood plain regulation, and flow forecasting and flood control. HEC-HMS demonstrated its capability in simulating water quantity but water quality cannot be determined in this model. Impact of tiles in sub-soil is also not considered (Scharffenberg and Fleming, 2010).

PRMS is a deterministic, distributed parameter, physical process based modeling system developed by USGS to evaluate general watershed hydrology. The effects of variability in climate, geology, landuse and human activities on water availability can be estimated at watershed scale. Integration of PRMS with natural resource management tools enhances its application spectrum but it is unable to simulate water quality parameters which limit its applicability for determining microbial or pollutant loadings (Leavesley et. al., 1983).

ANSWERS is a distributed parameter, physically based, continuous simulation model for predicting sediment and nutrient contribution from urban and agricultural areas in streamflow. But model does not consider snow pack and snow melt routines, which restrict its application in areas where snow processes regulate hydrology significantly (Dillaha et. al., 2004).

Among all models, SWAT and HSPF have been extensively used for simulating microbial total maximum daily loads. HSPF finds better application in urban watersheds while SWAT is used mainly for agricultural watersheds. HSPF can simulate runoff at hourly time steps whereas SWAT simulates at daily basis. Bacteria loading rate (cfu/ha/h) in HSPF is specified directly which may be constant or vary on monthly basis, while in SWAT it is specified as product of bacterial content of manure (cfu/g) and manure loading rate (kg/ha/d) in HRU at a constant or daily variable rate. But SWAT has more potential over other softwares due to its ability to simulate tile flow and bacterial loading (Coffey et. al., 2007, Neitsch et. al., 2005 and Bicknell et. al., 2001).

2.5 Soil and Water Assessment Tool

SWAT is a process based lumped parameter model developed by USDA Agricultural Research Service for modeling hydrological, sediment, nutrient, bacterial, and tile drainage processes. SWAT is employed to simulate hydrological processes on long term basis instead of a single storm event. It is used extensively to understand the hydrology of diverse geographical features. SWAT is extension of SWRRB model. CREAMS, GLEAMS and EPIC were later incorporated into this advanced model enabling it to simulate chemicals, runoff, erosion and groundwater. Reservoir and pond storage modules were added to determine their impact on water routing. Nutrient transport and loading components were imported from SWMM along with regression equations from USGS. Nutrient water quality equations were included from QUAL2E model. In SWAT 2000 version bacteria fate and transport routines were added along with Green & Ampt infiltration method and Muskingum Routing method. Sadeghi and Arnold (2002 and 2002) developed microbial module which allows it's partitioning into adsorbed and non-absorbed phase. SWAT 2009 was further improved by adding sub-daily precipitation weather generator and improved microbial transport equations. Various best management practices features were also integrated to estimate their impact on hydrology and water quality. SWAT interfaces for Windows, GRASS and ArcView were developed to expand its application scope (Di Luzio et. al., 2004).

Digital Elevation Model (DEM) is used to delineate watershed and further division into sub-watersheds based on one reach per sub-watershed. Then each sub-watershed is again divided into HRUs (Hydraulic Response Units) based on uniform landuse, soil and slope factors. These HRUs are lumped together to give overall water yield for each sub-watershed. Precipitation, Maximum & Minimum Temperature, Relative Humidity, Solar radiation and Wind Speed daily or sub-daily information is used to simulate the weather conditions. If this data is not available then in-build weather generator can be used to simulate these values. Different agricultural practices can be opted to mimic the actual landuse and management scenarios. Major component of water balance are surface runoff, groundwater flow, evapotransportation and reservoir storage. The resulting water enters river and is routed till the watershed outlet. After performing water balance sediments, nutrients, insecticides, pesticides and microbial transport can be simulated as all other processes are dependent upon effective water transport.

Results are generated on daily, monthly or annual basis. Most sensitive parameters that govern the critical processes of watershed are determined by performing sensitivity analysis. Calibrated is performed by changing these selected parameters. Simulated results obtained by modifying parameters are compared with actual monitored values to measure the synchronization of model processes with real conditions. Various statistical tools like multiplicative form of square error, summation form of square error, coefficient of determination, chi-squared, Nash-Sutcliffe coefficient, SSQR etc. can be employed to determine the accuracy of model predictions. After reaching the desired efficiency the calibrated model can be validated against another monitored data set from different period.

Bacterial fate and transport processes are simulated for soil, sediment and stream. Earlier fecal coliform bacteria was considered as bacterial indicator but recent researches have shown that Hepatits A viruses, Norwalk, salmonella and Cryptosporidium have caused waterborne disease even though the indicator bacterial levels were found to be low. Thus SWAT allows persistent and non-persistent microbial modeling approach with two different species of pathogens that have different growth and death rates. Chick's Law as described by equation 2.4 is used to model the two bacteria populations present on the foliage, in soil solution and attached to the soil particles (Reddy et. al., 1981, Crane and Moore, 1986 and Moore et. al., 1989).

$N_t = N_0 \times 10^{-\mu t}$ Equation 2.4

Where: N_t is Number of bacteria at any given time t (cfu), N_0 is Initial number of bacteria (cfu), μ is Decay constant (day^{-1}), and t is Time (days).

The bacteria die-off constant is temperature dependent and its value at different temperatures can be calculated by equation 2.5:

$\mu = \mu_{20} \times \Theta^{T-20}$ Equation 2.5

Where: μ_{20} is Die-off constant at 20 ℃ (day^{-1}), Θ is Temperature adjustment factor, T is Temperature (℃)

Bacteria present in top 10mm soil layer in solution are susceptible to percolate into soil layers and SWAT assumes decay of bacteria is deeper soil layer. The bacteria flow in tile drainage is also not simulated in SWAT.

Bacterial transport in surface runoff is simulated from microbial pool in soil solution and microbes attached to sediments. For each storm event, the sediment attached bacterial transport is estimated based on enrichment ratio which is the ratio of concentration of bacteria that gets transported along with sediment to the concentration of bacteria attached to the soil particles in top layer. For each of the storm events enrichment ratio is calculated in which it is logarithmically related to sediment concentration by equation 2.6:

$$\varepsilon = 0.78 \times C^{-0.2468} \qquad \text{Equation 2.6}$$

where: ε is Enrichment Ratio, C is Concentration of sediment in surface runoff (Mg sed/m^3)

In larger watersheds where time of concentration is greater than one day, all the runoff will not reach main stream on same day as it is generated. For such cases, SWAT provides a storage feature to lag part of runoff as well as bacterial release to main stream. Bacterial die-off is the only process considered for microbial modeling in stream and water bodies.

SWAT application in microbial modeling is limited as compared to vast implementation in hydrology and pollutant transport. SWAT was applied on two rural watersheds within the Grand River Basin in Ontario. Six months of field monitoring data (hourly water level and semi-weekly total coliform and *E. coli* data) was used to calibrate the model. SWAT was able to capture seasonal *E. coli* trends, but it failed in accurately representing field conditions (Mocan, 2006).

Frey et. al. (2013) observed that SWAT model adequately simulated streamflow, nitrogen and phosphorus loading, but was not able to capture total suspended solids, fecal coliform, and *E. coli* loading. SWAT model was also insensitive to observed reduction in the cattle population.

Arnold et. al. (2012) reviewed calibration and validation techniques, most sensitive parameters for different components of water budget, pollutants and nutrients. It also provided detailed description of steps to be followed for calibration and uncertainty analysis.

Parajuli et. al. (2008) quantified and evaluated the effect of vegetative filter strip on sediment and fecal coliform loading. They found that targeted approach reduced 60% while random approach reduced 42% of bacterial loadings.

2.6 Summary

In this chapter watershed hydrology, water budget, water quality issues and modeling aspects were discussed. It provided thorough understanding of various components required for addressing challenges stated in problem definition and designing medthodology to meet study objectives. The major challenges related to water quality were diagnosed as non point sources for sediment and pathogen plollution in surface water.

The SWAT model was selected based on literature reviewed for performing water quantity and quality analysis. Most sensitive parameters related to water flow, sediment and pahogen transport will be determined by perfoming sensitivity analyses. Water budget analysis will be performed to understand the quantitative distribution of water as fate and transport of pollutants is depedent upon fluvial processes. The seasonal variation and trend analyses of contaminat loading will be performed. Source identification and sub-watershed contribution would also be discussed in susequent chapters.

CHAPTER 3

METHODOLOGY

3.1 Model Development

ArcGIS based Soil & Water Assessment Tool (SWAT) was employed for developing conceptual hydrological model to perform water budget analysis and load estimation for Canard River Watershed. SWAT was preferred over other models due to its ability to simulate hydrological, sediment, nutrient, pesticide and bacterial processes including agricultural management practices and tile drainage component on a continuous, daily basis.

3.2 Site Description

Essex County is located at the southernmost region of Ontario. It is bounded on three sides by Lake St. Clair (north), Detroit River (west), and Lake Erie (south) while its eastern boundary is shared by Lower Thames Valley Conservation Authority. Essex County has nine municipalities, out of which seven (Town of Amherstburg, Town of Essex, Town of Kingsville, Town of Lakeshore, Town of LaSalle, Town of Leamington, and Town of Tecumseh) falls under County of Essex while other two (City of Windsor and Township of Pelee) are independent. Essex County is divided into approximately 24 sub-watersheds.

Climate of this region is influenced by “Lakes Effect Snowfall” as well as “Urban Heat Island Effect” due to its proximity to Lake Erie and Detroit City (AquaResource, 2013 and Sanderson, 1980). It witnesses four seasons namely winter, spring, summer and fall. Essex County is better known as “Solar Parlour of Canada” as it enjoys warm long summer and cool short winter as compared to rest of Canada (Sanderson, 1980). It receives precipitation in all forms i.e., snow, rain, hail, mist, and sleet. Average annual precipitation is 850 mm out of which 47% occurs between May to September. Average temperature ranges from less than -19 °C during winter while 34 °C during summer. The highest temperature occurs in July while the lowest temperature occurs in January (ERCA, 2011).

Canard River Watershed is the largest sub-watershed in this county encompassing 320 km^2 and draining water into Detroit River. It is spread across six municipalities namely Municipalities of LaSalle, Amherstburg, Essex, Kingsville, Lakeshore, and Tecumseh. Natural topography of the land surface is flat. Elevation ranges between 175 to 197 masl. The soil is mostly clay and has poor natural drainage. Natural vegetation is prairie grasslands but it was cleared after human settlement. Currently agriculture is practiced on major portion of this sub-watershed accounting for 96% while urban and all other land uses occupy approximately 4% only. Three chief crops grown include corn, winter wheat, and soybean.

There are 18 weather monitoring stations within Essex County but only 5 stations (Windsor Airport, Windsor Riverside, Amherstburg, Harrow CDA Auto, and Kingsville MOE) are currently under operation and remaining were closed (Climate Canada 2013). Out of these primarily Windsor Airport, Harrow CDA Auto, and Amherstburg have significant data and lie near Canard River Watershed. Lukerville monitoring station is located on Canard River that monitors streamflow and flow levels on daily basis. The location of Canard River Watershed is shown in Figure 3.1.

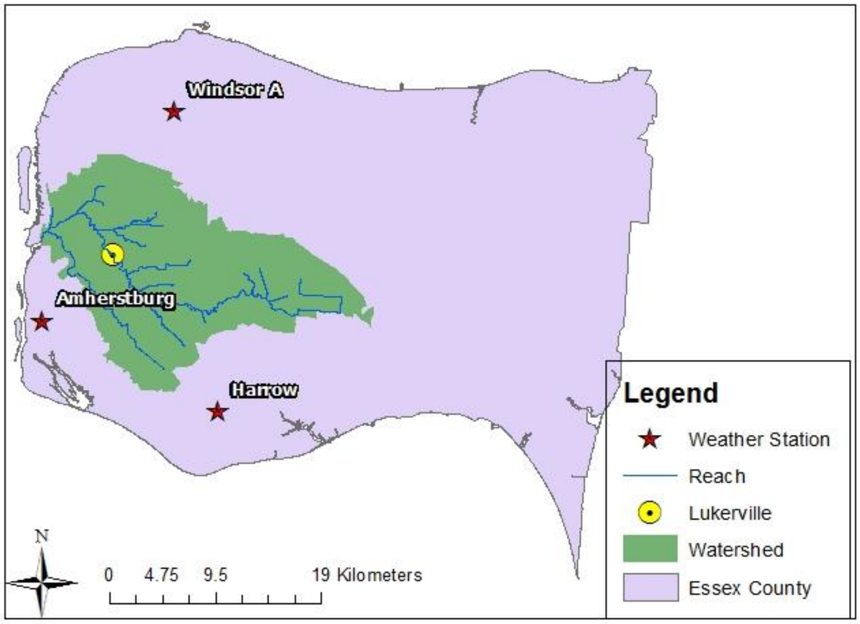

Figure 3. 1: Location of Canard River Watershed

3.3 Data Acquisition

Hydrological modeling with SWAT model requires details of spatial and temporal distribution of climate variability; along with topographical, soil characteristics, land use and management practices, and observed water quantity and quality information. The required data is monitored and collected by different agencies. Detailed information on the sources and description is provided in Table 3.1.

Table 3. 1:Data Sources

Type	Source	Description
Topography	Ontario Geospatial Data Exchange (OGDE)	Digital elevation model
Stream Network	Scholars Geo Portal	Drainage Network
Soil	CANSIS- Canadian Soil Information System	Soil classification and physical properties
Land use	Scholars Geo Portal	Land-use classification
Tile Drainage	Land Information Ontario (LIO)	Tile Drained Areas
Crop and Agricultural Practices	Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA)	Crop types, timings, practices, and area under each crop
Climate	Environment Canada – Historical Climate Data	Precipitation, air temperature, solar radiation, humidity, and wind speed
Hydrology	Environment Canada	Streamflow
Sediment	Environment Canada - HYDAT Database	Sediment concentration
Livestock	Statics Canada	Cattle and Horse
Municipal Sewer Boundary	Municipalities of La Salle, Tecumseh, Lakeshore, Amherstburg, Essex, and Kingsville	Areas under municipal sewer network
Migratory Birds	Environment Canada	Canada Geese
Wildlife	Ontario Ministry of Natural Resources	White tailed deer and Raccoon

3.3.1 Climate Data

SWAT requires daily and climate normal data for precipitation, minimum and maximum temperature, wind speed, relative humidity, and solar radiation for simulating climate distribution within the watershed. Along with this it also needs the geographical location of weather stations. These data were obtained from Environment Canada’s website (Climate Canada, 2013 and Canadian Climate Normals, 2013) and missing data gaps were filled from nearby station data. All stations have precipitation and temperature daily data but only Windsor Airport station has wind speed and relative humidity hourly data.

This hourly data were averaged into daily data and substituted for missing data in other stations as well. The detailed information is provided in Table 3.2.

Table 3. 2: Climate Station Data

Name	Latitude	Longitude	Elevation (m)	Data used for Modelling	Period of Record
Windsor A	42 °16'32.0" N	82 °57'20.0" W	189.6	Precipitation, Temperature, Wind Speed, Relative Humidity	1940-2014
Harrow CDA Auto	42 °02'00.0" N	82 °54'00.0" W	191.0	Precipitation, Temperature	2000-2014
Harrow Automatic Climate Station	42 °02'00.0" N	82 °54'00.0" W	190.5	Precipitation, Temperature	1992-2000
Amherstburg	42 °06'12.1" N	83 °05'40.1" W	182.0	Precipitation, Temperature	1988-2014

3.3.2 Digital Elevation Model (DEM)

The DEM file was obtained from the Ontario Geospatial Data Exchange (OGDE). It is a raster file in which each grid value represents the elevation at that location. Earth surface is divided into discrete rectangular tiles which can be combined together for analyzing larger geographical areas. But the entire Canard River Watershed lies under Tile 067, thus this particular file having 10 meter resolution was used alone. The DEM map is shown in Figure 3.2. DEM was used in SWAT to extract the watershed and then divide it into several sub-basins, stream network and monitoring points.

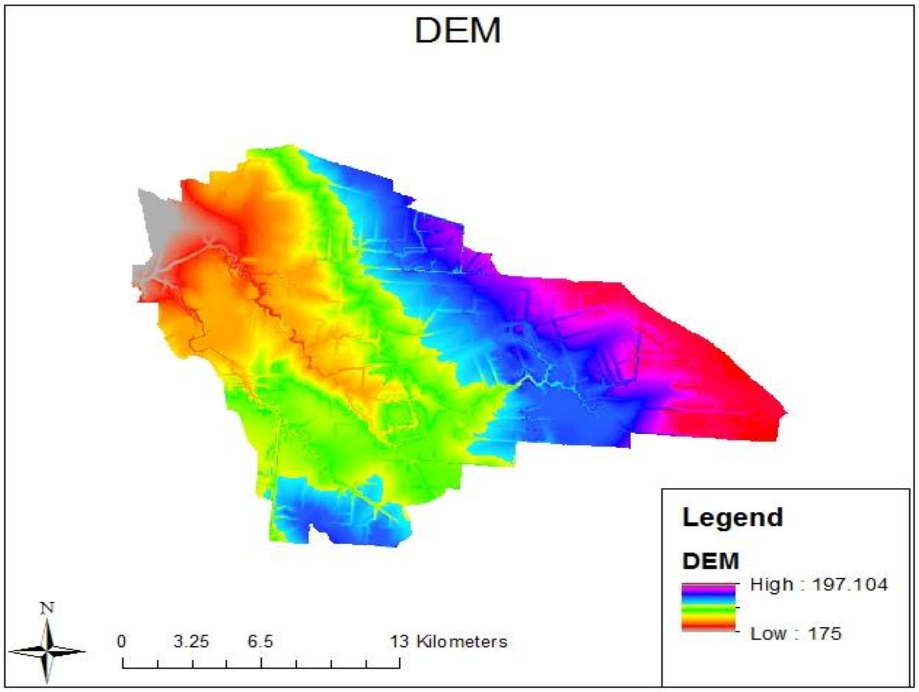

Figure 3. 2: Digital Elevation Model (DEM)

3.3.3 Soil Data

Hydrological processes in a watershed are greatly impacted by physical properties of soil. Different soil names, maximum rooting depth of the soil profile, number of soil layers, texture of the soil layer, depth from surface to bottom of soil layer, moist bulk density, saturated hydraulic conductivity of the soil layer, sand, silt, clay, rock and organic carbon content of the soil within the study area were obtained from the Canadian Soil Information System (CANSIS) (Agriculture and Agri-Food Canada, 2002). Available water content was calculated from corresponding soil texture and organic matter by using Soil Water Characteristic – Hydraulic Properties Calculator (Saxton, 2006). Moist albedo factor could be approximated based on soil color (Singh, 1999 and Post, 2000). Soil erodibility factors, K, for Universal Soil Loss Equation were estimated based on soil texture class and organic matter content of different soil types (Wilkes, 2004 and Stone and Hilborn, 2012). Total of 14 different soil types were found to be present in Canard River Watershed. Figure 3.3 shows, out of fourteen soil types present in this watershed, Brookston Clay, Brookston Clay Loam and Toledo Clay soils are the most predominant.

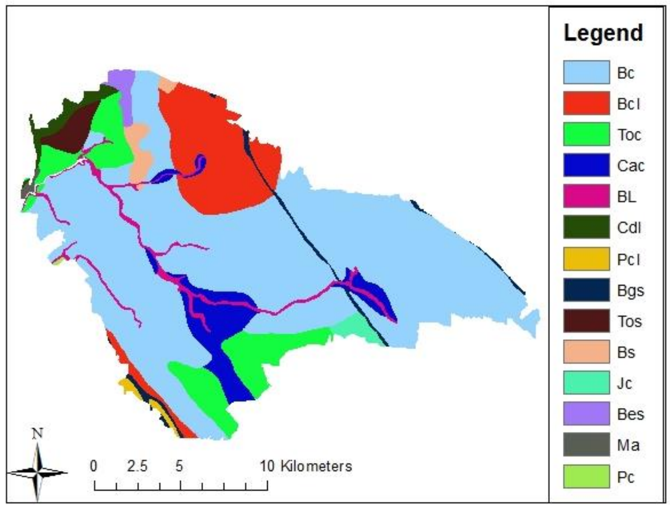

Figure 3. 3: Soils of Canard River watershed

3.3.4 Monitored Streamflow and Sediment Data

Lukerville Gaging Station is located within the watershed that monitors streamflow and water level on daily basis. Daily monitored data is available from Nov 1976 till Dec 2012 on Environment Canada's website. Streamflow values were required to calibrate the model. Model performance is validated by comparing the observed values with simulated results from calibrated model.

Limited sediment data obtained from grab samples collected over different periods is also available on Environment Canada - HYDAT Database website (Environment Canada – HYDAT Database, 2013).

3.3.5 Landuse and Tile Drainage

Landuse pattern shape file was downloaded from Scholars Geo Portal website. Agriculture, urban and pasture were found to be significant landuse patterns in Canard River Watershed. Out of this agriculture covers approximately 96% area while urban and pasture cover only 2.7% and 1.3% area shown in Figure 3.4. As this watershed has predominant land area under agriculture, thus the crop and management practices play most important role in determining the water budget and pollution loading rates.

Tile drainage GIS shape file was obtained from Landuse Information Ontario (LIO). The area under tile drainage in Canard River Watershed was extracted and it was found to be 174.36 km^2 out of 320 km^2. Thus 54.5% of watershed is under tile drainage which drains significant groundwater as shown in Figure 3.5.

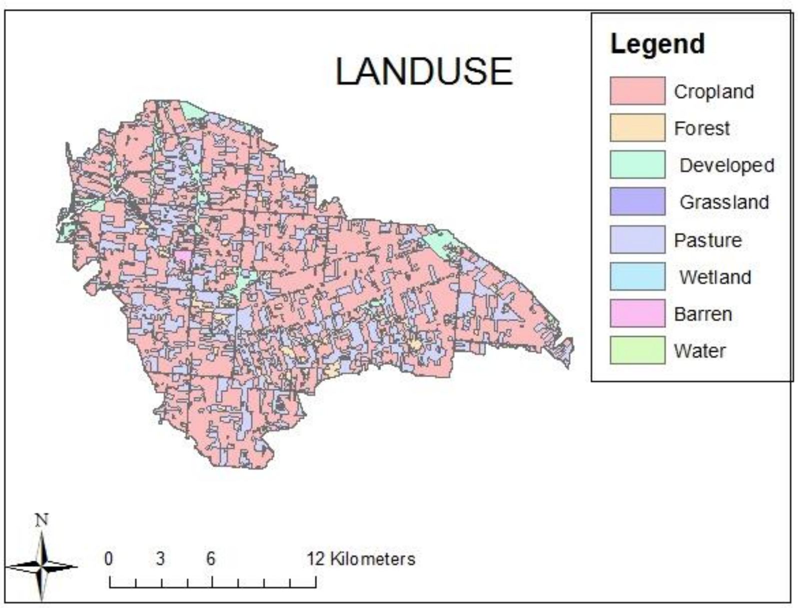

Figure 3. 4: Landuse Map of Canard River watershed

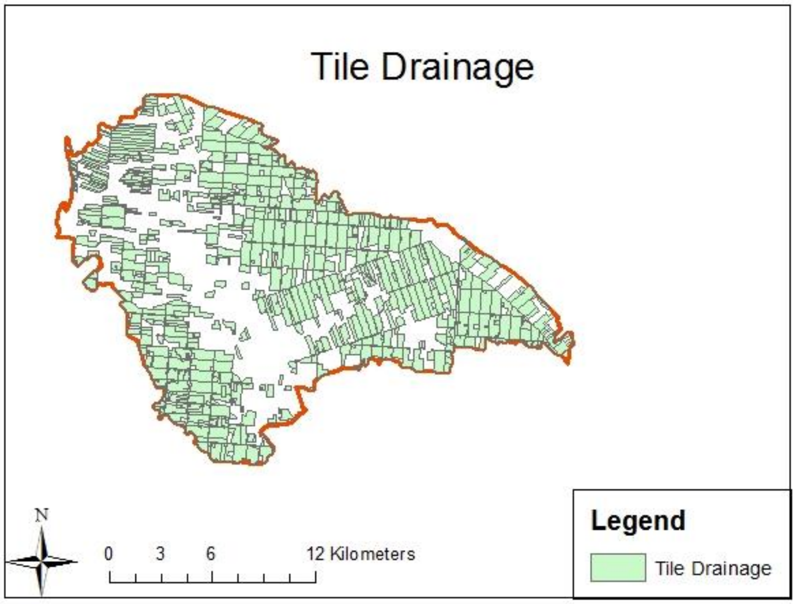

Figure 3. 5: Tile Drainage Map of Canard River watershed

3.3.6 Crop and Management Data

Soybean, winter wheat, corn are three major crops grown over 57%, 24% and 19% of the agricultural area respectively in Southern Ontario (Statistics Canada, 2011). Information related to different management operations practiced along with date of application is required. Tillage, planting, irrigation, fertilizer and manure application, pesticide application, and harvest time and other pertinent information were obtained from Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA Crops, 2014). Other crop parameters are already available in Arc SWAT and predefined values were used for simulation. Single crop is grown in a year within this region. Crop rotation is practiced with corn or wheat followed by soybean and also corn followed by wheat is frequently implemented.

Tillage - Conventional tillage is practiced while cultivating corn while no till is applied in case of wheat and soybean.

Plantation - Winter wheat is planted between mid – September to mid – October. Soybean is planted between mid - May to early – June. Corn is planted between early – May to mid – May.

Fertilizer application – 8.8 Kg/Ha of Phosphorus and 70 Kg/Ha of Nitrogen fertilizers are applied to winter wheat. 13.2 Kg/Ha Phosphorus is applied to Soybean. 22 Kg/Ha of Phosphorus and 140 Kg/Ha of Nitrogen fertilizers are applied to Corn.

Harvest – Winter wheat is harvested in late July. Soybean is harvested during October. Corn is harvested during October to November.

Irrigation – Irrigation is generally not practiced in this region.

Tile Drainage – Approximately 55% of area has installed tile drains, which drain out excess soil water and make ground fit for plant growth.

Manure application – 700 meters buffer zones surrounding cattle and horse farms were assumed to receive manure originating from livestock. No grazing operation was selected as only 1.3% of land use was under pasture, which was considered insignificant. Thus whole manure produced from livestock rearing was assumed to be applied on agricultural fields.

3.3.7 Microbial Source Data

Faulty septic tanks, livestock manure application, wildlife, and migratory birds were presumed to be the significant source of pathogens in this watershed. As most of the houses lie outside municipal boundaries and have septic tanks also agriculture is main occupation and livestock manure is applied in fields to enrich soil fertility. Forested areas are not present but wild animals living in woodlands and in fields contribute towards pathogen loadings. Migratory birds especially Canada Geese graze in this region and could also be a significant source of pathogens. Thus the data collected for these categories from various sources is discussed in the following section.

3.3.7.1 Livestock Data

Livestock data was obtained from Statistics Canada website (Statistics Canada, 2011). This data contains information related to number of farms reporting livestock and total number of animals for each municipality within the Essex County. This information is provided in Table 3.3.

Table 3. 3: Livestock Data

	Cattle and calves on May 10, 2011			Horses and ponies on May 10, 2011		
	Farms reporting	Number	Avg	Farms reporting	Number	Avg
Kingsville	21	1006	48	21	91	4
Essex	13	454	35	31	296	10
Amherstburg	10	180	18	13	100	8
Tecumseh	7	Not Reported		10	216	22
Lakeshore	29	1638	56	30	225	8
		Avg/farm	40		Avg/farm	10

The specific details about farms and animals in each farm were not provided due to confidential issues, thus it was assumed that each farm has equal number of livestock. The average cattle and horse for each farm were estimated to be 40 and 10 animals, respectively.

3.3.7.2 Septic Tanks

Municipalities provide sewer facilities only to limited houses lying in urban areas, rest houses in rural areas are having septic tanks as per regulations. The maps delineating areas served by sewer network for each municipality were procured from reports and websites, and houses lying outside those boundaries were assumed to have septic tanks. Average flow of 450 l/capita/day from each house and average 3.5 persons per household were assumed based on The Corporation of the Town of Amherstburg (2009). Septic tanks distributing effluent directly into the stream are only significant contributors (Parajuli et. al., 2009). Thus the septic tanks lying within 30 meters from drainage line were assumed to contribute to pathogen loading due to faulty leakage (Fall, 2011). Total septic tanks within each sub-basin are presented in Table 3.4.

Table 3. 4: Septic Tanks in each Sub-Watershed

Sub-Basin	Number of Septic Tanks	Sub-Basin	Number of Septic Tanks	Sub-Basin	Number of Septic Tanks
1	4	13	0	25	2
2	17	14	0	26	9
3	20	15	7	27	15
4	9	16	20	28	8
5	10	17	1	29	38
6	12	18	34	30	3
7	13	19	14	31	23
8	23	20	2	32	69
9	2	21	25	Total	404
10	2	22	0		
11	0	23	14		
12	8	24	1		

3.3.7.3 Wild Life

According to Simon (2011), White –tailed Deer, Raccoon, Coyote, and Meadow Vole are most commonly observed mammalian species in Essex County. Out of these White-tailed Deer and Raccoon were found to have significant population based on Ministry of Natural Resources Reports. Thus they were considered as potential contributors for pathogen loading. There was no exclusive survey conducted for enumerating their population in Essex County. Broad range density ranges are available on Cervid Ecological Zone Scale. It was found that White-tailed Deer has moderate (200 – 500/100km^2) to high (500-1000/100km^2) population density in Essex County. Therefore on an average 500/100km^2 animal density was assumed (Ontario Ministry of Natural Resources, 2009). Raccoon density ranges from 3.4 to 13.6 km^2 in Southern Ontario. Agricultural areas with crop cover more than 75% were observed to have 9 raccoons per km^2 on an average (Rosatte, 2010).

3.3.7.4 Migratory Birds

Canada Goose and Cackling Goose are migratory birds that migrate through this region. They graze on cropland and pastures. Until recently, they were recognized as single breed. So their population ranges were estimated together. The population range for Southern Ontario lies between 0.5 to 5 geese per hectare. The average population density for this watershed was assumed to be 2.5 per hectare (Canadian Wildlife Service Waterfowl Committee, 2012).

3.3.7.5 Microbial Loading from Different Sources

Fecal production, *E. coli* and fecal coliform concentration for each source are presented below in Table 3.5.

Table 3. 5: Microbial Loading from Different Sources

Source	Fecal production	*E. coli*	Fecal coliform	Manure Application
Cattle	18.14 kg/AU/day	3.52 X 10^5 cfu/g	1.06 X 10^6 cfu/g	4.72 kg/ha/d
Horse	18.6 kg/AU/day	1.2 X 10^5 cfu/g	1.3 X 10^4 cfu/g	1.21 kg/ha/d
White-tailed Deer	6.8 kg/AU/day	4.3 x 10^5 cfu/g	4.5 X 10^5 cfu/g	0.18 kg/ha/d
Raccoon	0.11 kg/AU/day	9.59 X 10^6 cfu/g	2.5 X 10^5 cfu/g	0.01 kg/ha/d
Canada Goose	0.25 kg/AU/day	1.43 X 10^5 cfu/g	1.53 X 10^5 cfu/g	0.61 kg/ha/d
Septic Tank	450 l/capita/day	6 X 10^7 cfu/l	1 X 10^8 cfu/l	450 l/capita/d

3.4 Arc SWAT Model Setup

Climate data, DEM file, soil shape file, landuse shape file, information related to weather stations, monitoring stations and agricultural practices were processed. Necessary data was prepared as GIS layer files and incorporated into ArcGIS interface i.e. ArcSWAT of Soil and Water Assessment Tool (SWAT) Model. Its interface with GIS allows use of Spatial Analyst Module that enhances its analytical and operational abilities several folds. Following steps were followed for setting up the model.

3.4.1 Watershed Delineation

DEM file with 10 meter resolution, containing the entire area of watershed and monitoring station shape file having location of Lukerville were added in ArcSWAT. Automatic watershed delineator tool of ArcSWAT was used to delineate watershed. Flow direction, accumulation and stream network were created. It also generated the reaches, monitoring points and outlet points for reaches shown in Figure 3.6.

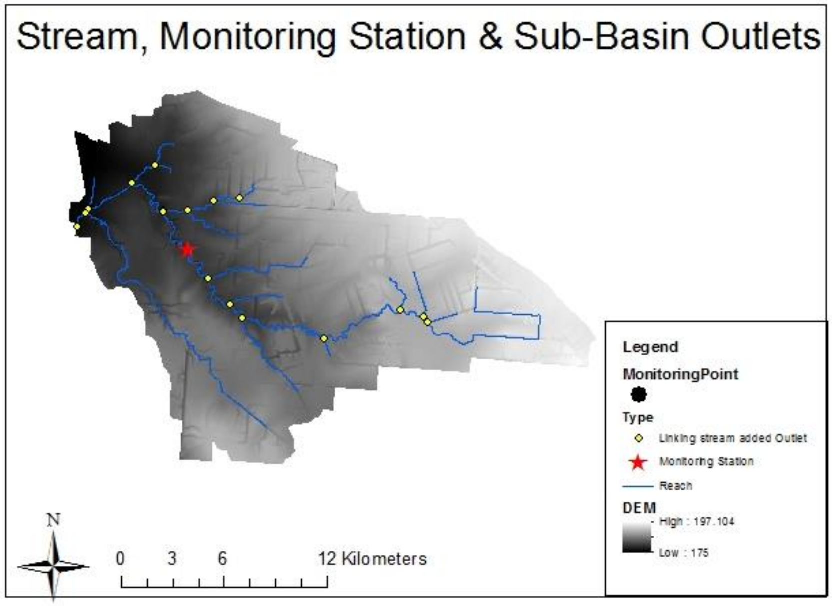

Figure 3. 6: Stream, Monitoring Station and Sub-basin outlets

Flow monitoring station location was added manually based on the shape file containing Lukerville monitoring station location as sub-basin outlet. Septic tanks were added as point sources for each sub-basin. In the next step, the last point on stream network was selected as whole watershed outlet to delineate the watershed. Total 32 sub-watersheds were created as shown in Figure 3.7.

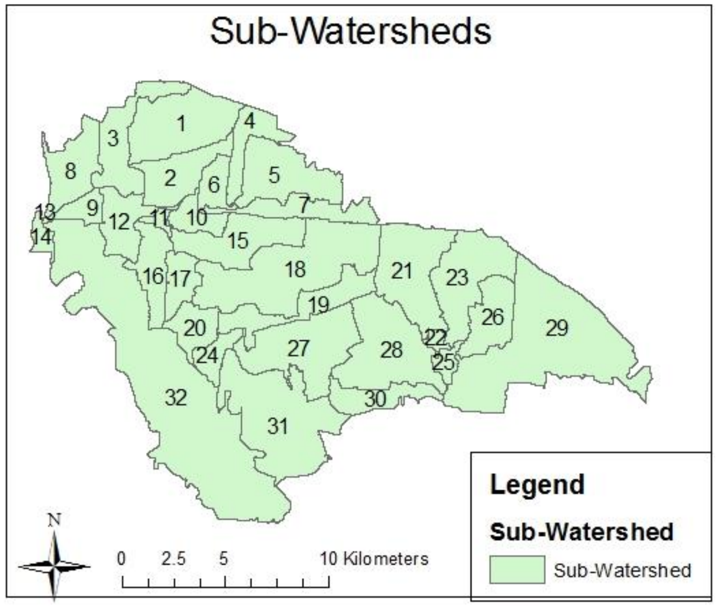

Figure 3. 7: Delination of watershed and sub-watersheds of Canard River watershed

3.4.2 Hydrological Response Units (HRUs)

HRUs are areas within the watershed that has same soil type, land use, and slope. Their hydrological behavior is same as given inputs. Sub-basins were further divided into different HRUs based on uniformity of land use pattern, soil types and slope.

Tile drained areas were combined with original landuse file to generate new shape file projecting exclusively tile drained agricultural areas. The locations of livestock farms were later incorporated in newly created shape file and 700 meter buffer zone was allotted around cattle and horse farms where manure was assumed to be applied.

Land use and soil type shape files were converted into raster files with cell size of 10 meter resolution i.e., same as DEM file (all raster files should have same grid resolution in order to be processed by SWAT). As SWAT is lumped tool, so each HRU contributed directly to the stream. Lookup tables were created for these particular layers in text files for reclassifying the original land use categories and soil types. Agriculture is major category with 95.92% of total area. In case of soil types, there are fourteen different types of soils in this watershed dominated by Brookston Clay covering 62.33% of the entire area followed by Brookston Clay Loam Soil having 10.87% watershed area.

As each area may have unique characteristics which may lead to creation of too many unique HRUs and their simulation may become more complex and time consuming. Thus to limit their number a particular threshold value of ten percent for landuse and soil was selected and multiple HRUs were created within each sub-basin. The land use and soil types having less than ten percent area within each sub-basin were not selected for creation of HRUs.

3.4.3 Land Management Operations

SWAT has default parameter values for crop growth, fertilizer, tillage, agricultural management practices in its database. Based on the information obtained from different sources as mentioned in previous sections these parameter values were selected from SWAT database. Tile drainage operation was selected for agricultural HRUs having tile drainage network. Depth of tiles was assumed to be 0.9 meters. Time to drain soil to field capacity was assumed to be 48 hours while drain tile lag time was fixed at 24 hours based on values suggested by Arnold et. al. (2012) and Fall (2011).

Manure application and bacterial concentration were added to database as calculated in previous section. Other than manure application parameters, the bacteria die-off, bacteria growth, bacteria partition coefficient and temperature adjustment factor were added to simulate microbial fate and transport in watershed based on ranges available in various researches (Bougeard et. al., 2011, Soupir et. al., 2010, Krometics et. al., 2009, Garcia-Arminsen and Servais, 2009 and Fall, 2011). Microbial parameter values used in model are shown in Table 3.6.

Table 3. 6: Microbial Parameters Values

Parameter	Definition	Range	Selected Value
WDPQ	Bacteria Die-off for persistent bacteria in soil solution	0 - 1	0.3
WDLPQ	Bacteria Die-off for less-persistent bacteria in soil solution	0 - 1	0.3
WDPS	Die – off factor for persistent bacteria attached to soil particles	0 - 1	0.03
WDLPS	Die – off factor for less persistent bacteria attached to soil particles	0 - 1	0.03
BACTKDQ	Growth factor for less persistent bacteria adsorbed to soil particles	0 - 500	175
THBACT	Temperature adjustment factor for Bacteria Growth / die-off	0 - 10	1.07
BACT_SWF	Fraction of manure applied to land areas that has active colony forming units	0 - 1	0.15
BACTMX	Bacteria percolation factor	7 - 20	10
WDPRCH	Die-off factor for persistent bacteria in stream (moving water) at 20 ℃	0 - 1	0.3
WDLPRCH	Die-off factor for less persistent bacteria in stream (moving water) at 20 ℃	0 - 1	0.3
WDPRES	Die-off factor for persistent bacteria in water bodies (moving water) at 20 ℃	0 - 1	0.4
WDLPRES	Die-off factor for less persistent bacteria in water bodies (moving water) at 20 ℃	0 - 1	0.4

3.4.4 Climate Data

Climate data of Windsor Airport, Amherstburg and Harrow stations was used to simulate weather input files. Precipitation, temperature, relative humidity and wind speed daily data from 1995 to 2013 were used. Due to non-availability of solar radiation data, its daily values were simulated using in-built weather generator.

The SWAT model simulation can be performed on daily, monthly or annual basis. For this study daily simulation was performed from 1995 till 2013. The model was then calibrated and validated as discussed in chapter four for ascertaining its accuracy. The calibrated model results were subjected to further analysis to meet the defined objectives and elaborately discussed in chapter five.

CHAPTER 4

CALIBRATION AND VALIDATION

Modeled water quantity and quality results are affected by a range of parameters. Simulated output based on default parameter values may not exactly match with observed variables. Calibration is performed by adjusting the most sensitive parameters for different variables until simulated results match with observed values to a satisfactory degree. Then model with modified parameters is validated by running for different time period and the consistency of observed and simulated values is ascertained.

4.1 Sensitivity Analysis

Sensitivity Analysis is a process of determining the parameters which significantly impact the model outputs. It is performed by changing the input parameter values and measuring the resulting change in output. In this study the sensitivity analysis was performed for streamflow, sediment and bacterial parameters.

4.1.1 Flow

The sensitivity of one parameter depends upon the relative value of other parameters, thus SWAT-CUP based Latin Hypercube Global sensitivity analysis was performed for flow. Based on the characteristics of watershed and literature reviewed, parameters in Table 9 were selected and their t-stat and P-value was determined. The t-stat gives measure of sensitivity; the parameter with higher absolute t-stat value has higher sensitivity. P-value provides information on significance of sensitivity; parameter having value close to zero has higher significance. Based on t-stat and p-value; these parameters were divided into three categories i.e. highly sensitive parameters, medium sensitive parameters and low sensitive parameters as shown in Table 4.1. The highly sensitive parameters corroborate with previous research performed in this watershed (Rahman, 2007).

Table 4. 1: Sensitivity Analysis for Flow Parameters

Parameter Name	t-Stat	P-Value	Sensitivity
SCS runoff curve number (CN2)	-2.99	0.00	High
Maximum canopy storage (CANMX)	3.30	0.00	High
Average slope length (SLSUBBSN)	3.91	0.00	High
Soil evaporation compensation factor (ESCO)	-4.11	0.00	High
Average slope steepness (HRU_SLP)	-4.56	0.00	High
Manning's "n" value for overland flow (OV_N)	5.31	0.00	High
Manning's "n" value for the main channel (CH_N2)	8.53	0.00	High
Surface runoff lag time (SURLAG)	-11.38	0.00	High
Snow pack temperature lag factor (TIMP)	-1.96	0.05	Medium
Average slope of tributary channels (CH_S1)	-2.07	0.04	Medium
Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN)	2.33	0.02	Medium
Minimum melt rate for snow during the year (SMFMN)	-2.46	0.01	Medium
Lateral flow travel time (LAT_TTIME)	-2.55	0.01	Medium
Maximum melt rate for snow during the year (SMFMX)	-0.12	0.91	Low
Groundwater delay (GW_DELAY)	-0.51	0.61	Low
Depth to subsurface drain (DDRAIN_BSN)	0.52	0.60	Low
Threshold depth of water in the shallow aquifer for "revap" to occur (REVAPMN)	0.62	0.54	Low
Plant uptake compensation factor (EPCO)	0.67	0.50	Low
Baseflow alpha factor (ALPHA_BF)	-0.71	0.48	Low
Time to drain soil to field capacity (TDRAIN_BSN)	0.74	0.46	Low
Groundwater "revap" coefficient (GW_REVAP)	-0.79	0.43	Low
Manning's "n" value for the tributary channels (CH_N1)	1.39	0.17	Low
Available water capacity of the soil layer (SOL_AWC)	1.61	0.11	Low

4.1.2 Sediment

Due to non-availability of sediment data for simulated period, manual one at a time sensitivity analysis was performed by changing the parameter values by ten percent and then observing the difference between default and modified results. The most sensitive parameters were determined by estimating the sensitivity index as presented in equation 4.1 (Lenhart et. al., 2002):

$$\text{Sensitivity Index} = \frac{(Y2 - Y1)/Y0}{2\Delta X/X0} \qquad \text{Equation 4.1}$$

where,

Y_0 and X_0 are original simulated output and input value of parameter,

Y_2 and Y_1 are new output values based on ΔX difference in input parameter.

The sensitivity analysis for sediment is presented in Table 4.2.

Table 4. 2: Sensitivity Analysis of Sediment Parameters

Channel Parameters	**Sensitivity**
Peak rate adjustment factor for sediment routing in the subbasin (tributary channels) (APM)	High
Peak rate adjustment factor for sediment routing in the main channel (PRF)	Low
Exponent parameter for calculating sediment reentrained in channel sediment routing (SPEXP)	Low
Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing (SPCON)	Low
Channel erodibility factor (CH_EROD)	Low
Channel erodibility factor (CH_COV)	Low

Land Surface Parameters	**Sensitivity**
Average slope length (SLOPE)	High
Min value of USLE C factor applicable to the land cover/plant (USLE_C)	High
Sediment concentration in lateral flow and groundwater flow (LAT_SED)	High
USLE equation soil erodibility (K) factor (USLE_K)	Low
Slope length for lateral subsurface flow (SLSOIL)	Low
USLE equation support practice factor (USLE_P)	Low

4.1.3. Microbial Parameters

SWAT's microbial sub-module simulates the processes involved in microbial fate and transport. These parameters include microbial growth and die-off in different environments, partitioning between soil and solution, temperature adjustment factor, and Fraction of manure applied to land areas that has active colony forming units. Due to non-availability of observed microbial concentration data for this watershed, manual one at a time sensitivity analysis was performed by changing these parameter values by ten percent and then the difference between default and modified results was analyzed to determine the sensitivity. The sensitivity analysis results are shown in Table 4.3.

Table 4. 3: Sensitivity Analysis of Microbial Parameters

Parameter	Sensitivity
Temperature adjustment factor for bacteria die-off/growth - (THBACT)	High
Die-off factor for less persistent bacteria in streams (moving water) at 20°C (1/day) - (WDLPRCH)	High
Die-off factor for persistent bacteria in streams (moving water) at 20 ℃ (1/day) – WDPRCH	High
Bacteria runoff extraction coefficient (m3/mg) – (BACTKDQ)	Low
Bacteria percolation coefficient – (BACTMX)	Low
Die-off factor for less persistent bacteria in soil solution at 20°C (1/day) – (WDLPQ)	Low
Die-off factor for persistent bacteria in soil solution at 20°C (1/day) – (WDPQ)	Low
Die – off factor for persistent bacteria attached to soil particles - (WDPS)	Low
Die – off factor for less persistent bacteria attached to soil particles - (WDLPS)	Low
Fraction of manure applied to land areas that has active colony forming units - (BACT_SWF)	Low
Die-off factor for less persistent bacteria in water bodies (moving water) at 20 ℃ - (WDLPRES)	Low
Die-off factor for persistent bacteria in water bodies (moving water) at 20 ℃ - (WDPRES)	Low

4.2 Calibration and Validation

Calibration is performed by changing the most sensitive parameter estimated from sensitivity analysis. It can be done either manually or by using auto-calibration tools by changing one parameter at a time or multiple variables at same time. Manual calibration is very labor intensive and time consuming process. Various researchers have performed auto-calibration by using Genetic Algorithms and Bayesian Approach (Zhang et. al., 2009), global optimization algorithms (Zhang et. al., 2008), genetically adaptive multi-objective method (Zhang et. al., 2009), and parallel processing by Sequential Uncertainty Fitting – SUFI 2 (Rouholahnejad et. al., 2012). SWAT CUP links Sequential Uncertainty Fitting version 2 (SUFI2), Generalized Likelihood Uncertainty Estimation (GLUE), Particle Swarm Optimization (PSO), Parameter Solution (ParaSol), Markov Chain Monte Carlo (MCMC) procedures to SWAT for calibrating and optimizing hydrological models (Abbaspour, 2013).

Monitored flow data for Lukerville monitoring station was used for performing auto-calibration by using SUFI2 algorithm from 2001 to 2006 on daily basis. Period from 1995 till 2000 was considered as warm up period. Most sensitive parameters i.e. SCS runoff curve number (CN2), Maximum canopy storage (CANMX), Average slope length (SLSUBBSN), Soil evaporation compensation factor (ESCO), Average slope steepness (HRU_SLP), Manning's "n" value for overland flow (OV_N), Manning's "n" value for the main channel (CH_N2), Surface runoff lag time (SURLAG) were selected and their minimum and maximum values were incorporated in SWAT-CUP for estimating best parameter values. Nash Sutcliffe Efficiency (NSE) was set as objective function for estimating the best fit parameter combinations as mentioned in equation 4.2:

$$Nash\ Sutcliffe\ Efficiency = 1 - \frac{\sum_{i=1}^{n}(Oi-Pi)^2}{\sum_{i=1}^{n}(Oi-\bar{O})^2} \qquad \text{Equation 4.2}$$

where,

O_i = Observed value

P_i = Predicted value

$\bar{O}$ = Average observed value

The NSE value ranges from -∞ to 1; -∞ represents no match while 1.0 signifies perfect match. The model was calibrated for years 2001 – 2006 and validated for period 2009 – 2012 on daily basis. The NSE value for calibration period was 50%, signifying a reasonable fit between observed and simulated values. The calibration plot for 2001 to 2006 is shown in Figure 4.1.

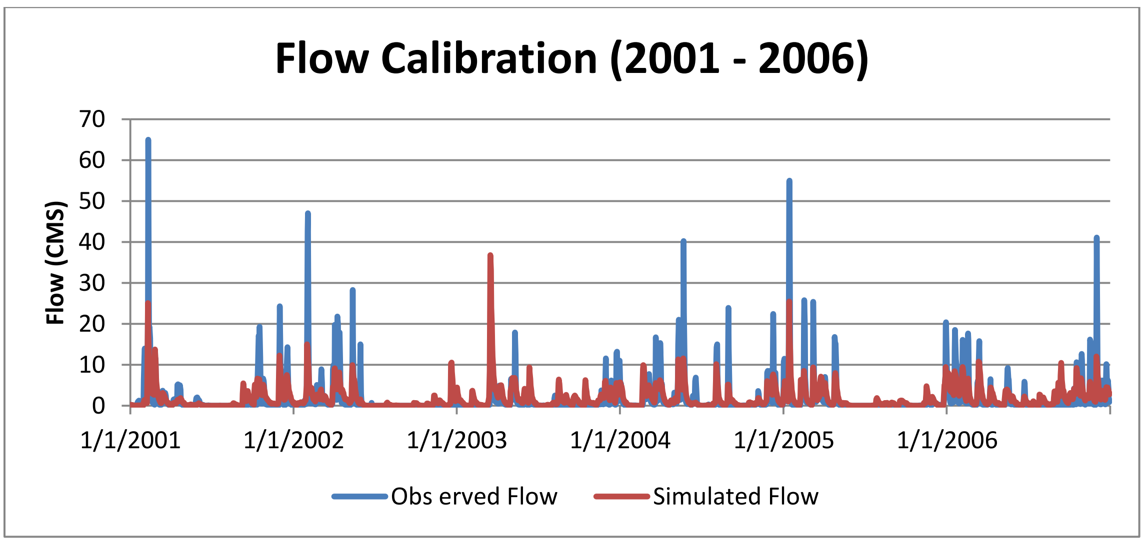

Figure 4. 1: Flow Calibration (2001 - 2006)

The calibrated model was then validated by running it for different set of years i.e. 2009 to 2012. The simulated results were compared against observed streamflow for same period and its accuracy was determined by calculating Nash Sutcliffe Efficiency. The NSE value for validation period was found to be 56.4% showing strong consistency between observed flow and modeled flow values. The validation plot for 2009 to 2012 is shown in Figure 4.2.

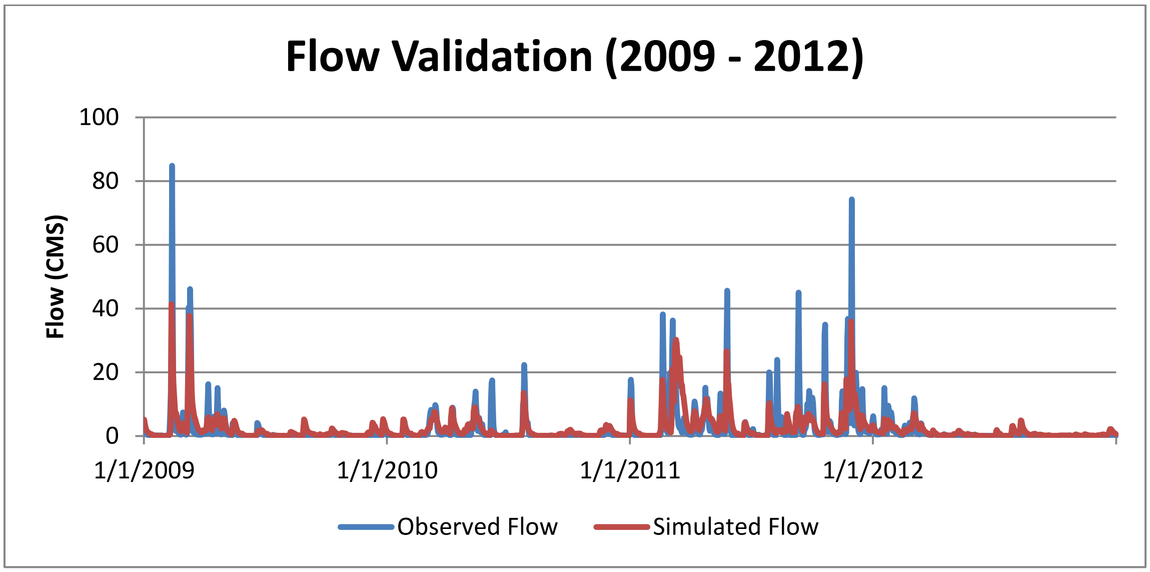

Figure 4. 2: Flow Validation (2009 - 2012)

The peak flow was found to be under predicted in model results for both calibration and validation periods. Further analysis on model output is discussed in next chapter.

CHAPTER 5

RESULTS AND DISCUSSION

The model simulated results are presented and discussed in this chapter under four sections. The discussion in this chapter is organized into four major sections – streamflow, water budget, sediment loading and *E.coli* loading. The outputs which include time series are presented on different time scales – daily, monthly, seasonal and annual. The first section includes the time series analysis of streamflow on annual, monthly and daily basis. The second section provides a broad overview on water budget. Water budget analysis was performed on annual, monthly and seasonal basis. Spatial distribution of different water budget components was also performed on sub-watershed scale. In third section sediment concentration ranges in different seasons was discussed along with loading patterns on annual and seasonal basis. The sediment yield from different sub-watersheds was also performed to determine the most significant areas prone to soil erosion. In the last section *E. coli* trends are provided on annual and seasonal time steps. In the absence of any data it is difficult to present the *E.coli* results on a finer time step. And at the end source characterization and contribution from different sub-watersheds is discussed.

5.1 Streamflow Time Series Analysis

The daily observed streamflow data from Lukerville monitoring station was used for performing time series analysis on daily, monthly, seasonal and annual basis. The results from the SWAT model are obtained on a daily time step and are summarized on different time scales.

5.1.1 Average Annual Flow Comparison

The comparison of observed and simulated annual average flows with annual precipitation was performed to verify the simulation accuracy and consistency of the model. Average annual flow comparison plot is shown in Figure 5.1 and the values are presented in Appendix Table A-1. The precipitation ranged between 712 and 1480 mm with an average 926 mm. The observed flow ranged between 0.64 m^3/s and 4.7 m^3/s with average flow of 1.78 m^3/s. The observed and simulated values showed high consistency for most years except 2003 and 2006, where observed flows were significantly lower than the simulated flows. Similar anomaly was observed by Rahman (2007) for the year 2003, indicating error in monitored data or highly localized precipitation events which were not recorded by the weather monitoring stations. Another interesting observation was made for the year 2011, which received very heavy precipitation as compared to other years, which resulted in significantly high observed and simulated flows.

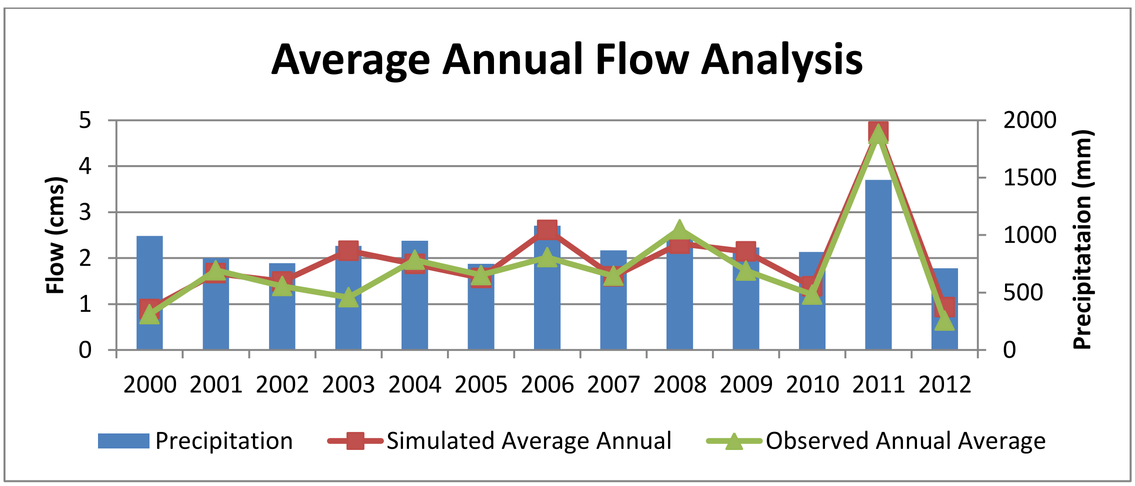

Figure 5. 1: Average Annual Flow Comparison

5.1.2 Seasonal Flow Comparison

Average monthly observed flow was compared with average monthly simulated flow as shown in Figure 5.2. Lower average precipitation was observed during winter while higher during spring. Significant variation in flow exists during different months as compared to variation in precipitation. The highest average monthly flow was observed and simulated during winter (January, February, March and December) especially during February and March followed by spring (April and May) and fall (October and November), while the lowest flows occurred during summer (June, July, August and September) especially during June and July. The values for average monthly and seasonal flow comparison are presented in Appendix Table A-2. The higher flows during winter and spring resulted from snow melt and reduced evapotranspiration, while higher evapotranspiration during summer resulted in reduced streamflow.

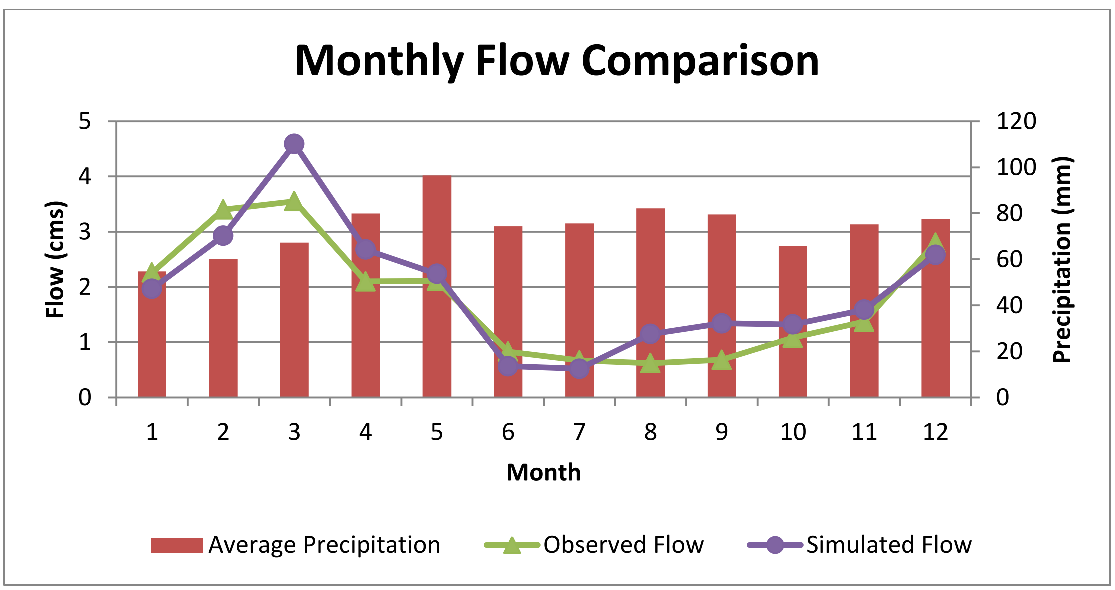

Figure 5. 2: Average Monthly Flow Comparison

5.1.3 Average Monthly Flow Time Series Comparison

Monthly flow comparison was performed for the calibration period (2001 - 2006) and validation period (2009 – 2012) as shown in Figures 5.3 and 5.4. The highest error was observed in March 2003, September 2006 and March 2011, where simulated values were significantly over-predicted. The maximum under prediction was observed in February and September of 2011.

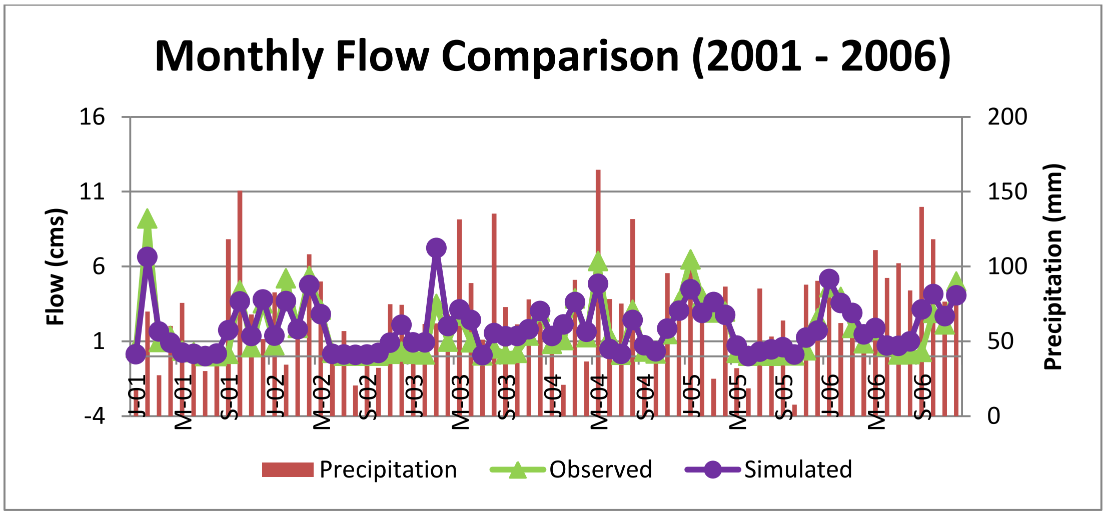

Figure 5. 3: Monthly flow comparison for calibration period

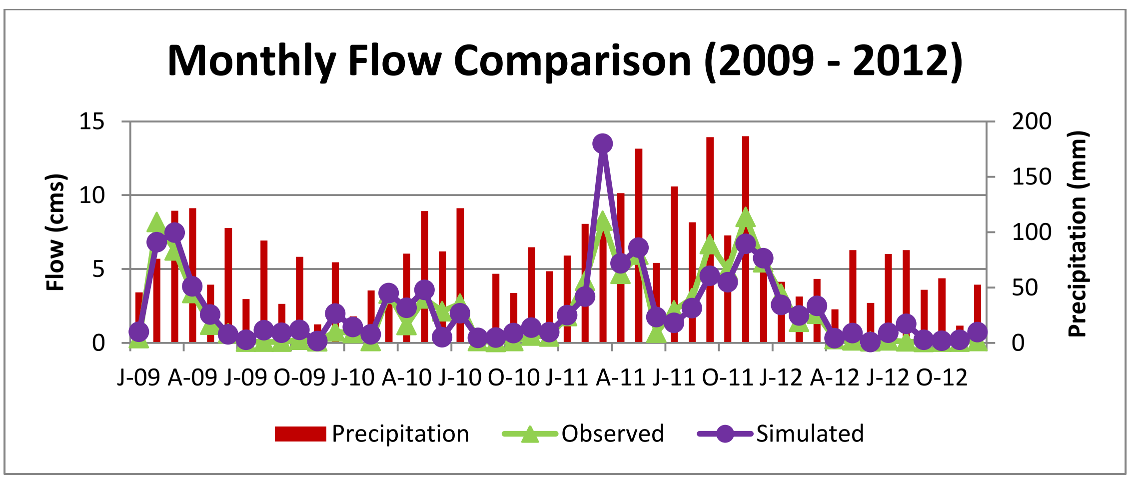

Figure 5. 4: Monthly flow comparison for validation period

5.1.4 Daily Flow Time Series Comparison

Higher simulated peaks coincide with observed flow peaks, while baseflow period was also captured well in model. The simulated peaks also followed precipitation peaks pattern for both calibration and validation periods as shown in Figures 5.5 to 5.14. The simulated peakflows were lower than observed peakflows. Similar pattern was observed in Fall (2011) daily observed vs simulated discharge results for calibration period where simulated peak discharge values were lower than the observed peak values. It suggested the model's inability to capture peak flows on daily time step simulation.

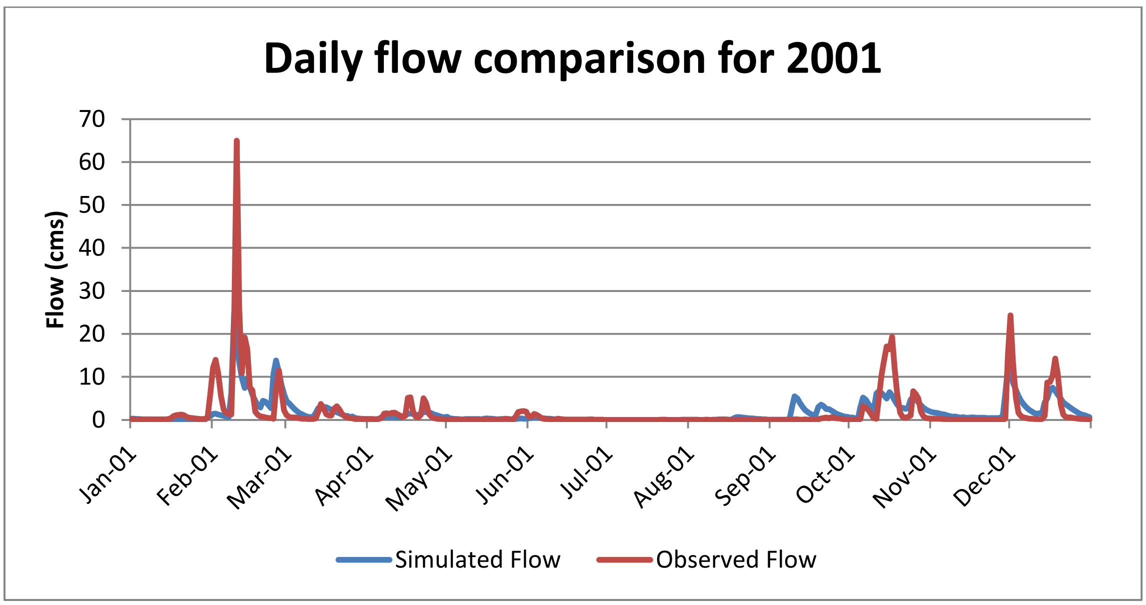

Figure 5. 5: Daily Observed vs Simulated Flow Comparison for 2001

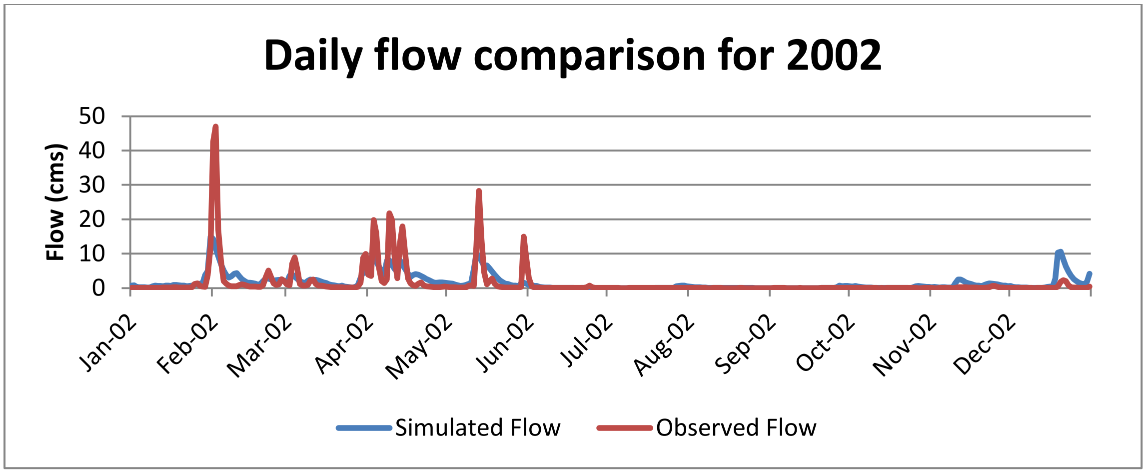

Figure 5. 6: Daily Observed vs Simulated Flow Comparison for 2002

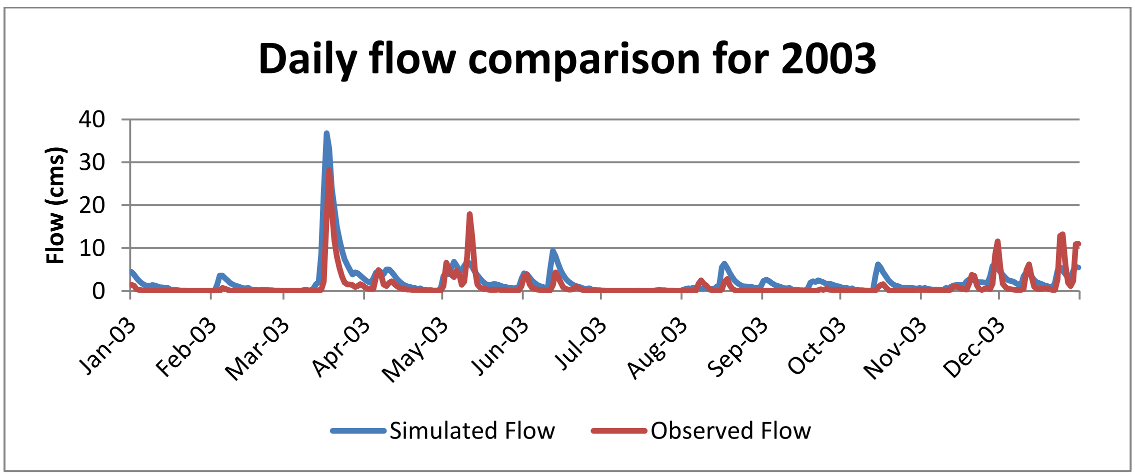

Figure 5. 7: Daily Observed vs Simulated Flow Comparison for 2003

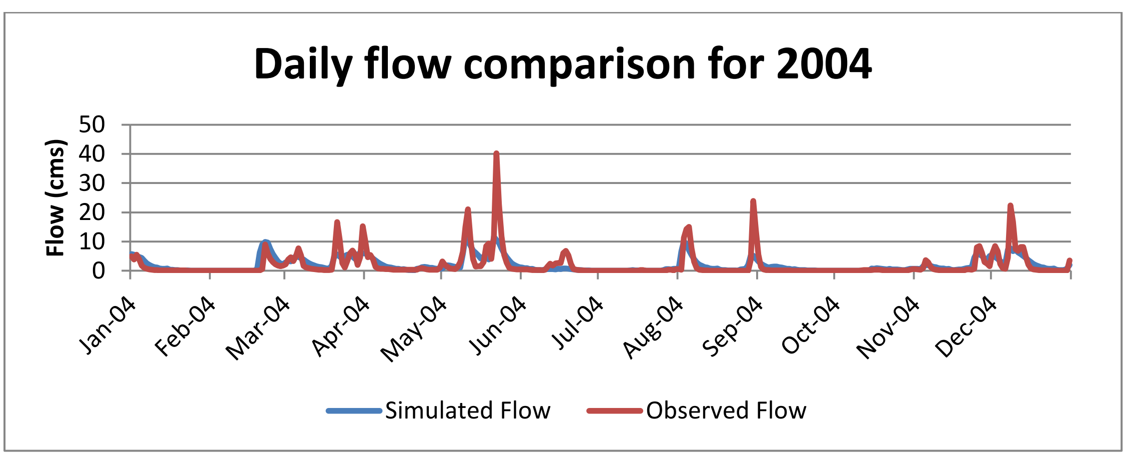

Figure 5. 8: Daily Observed vs Simulated Flow Comparison for 2004

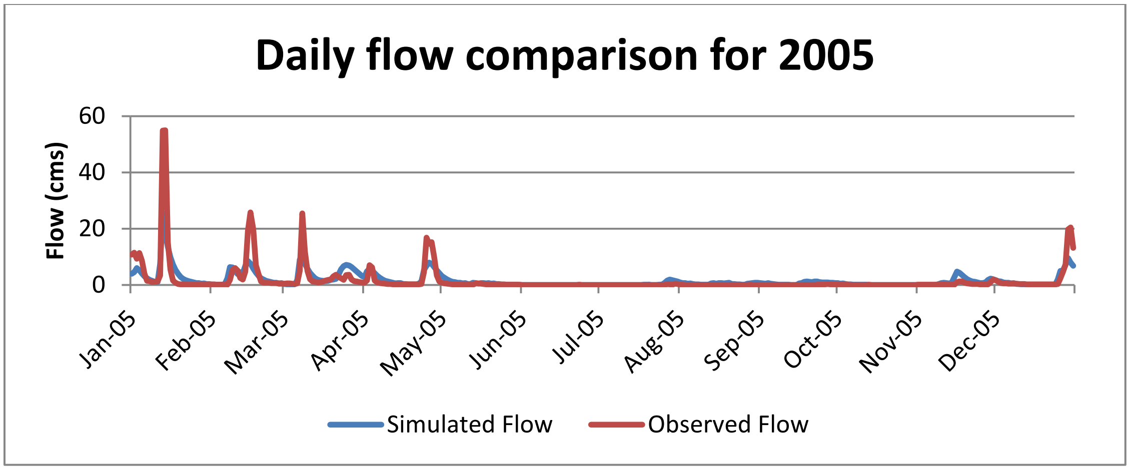

Figure 5. 9: Daily Observed vs Simulated Flow Comparison for 2005

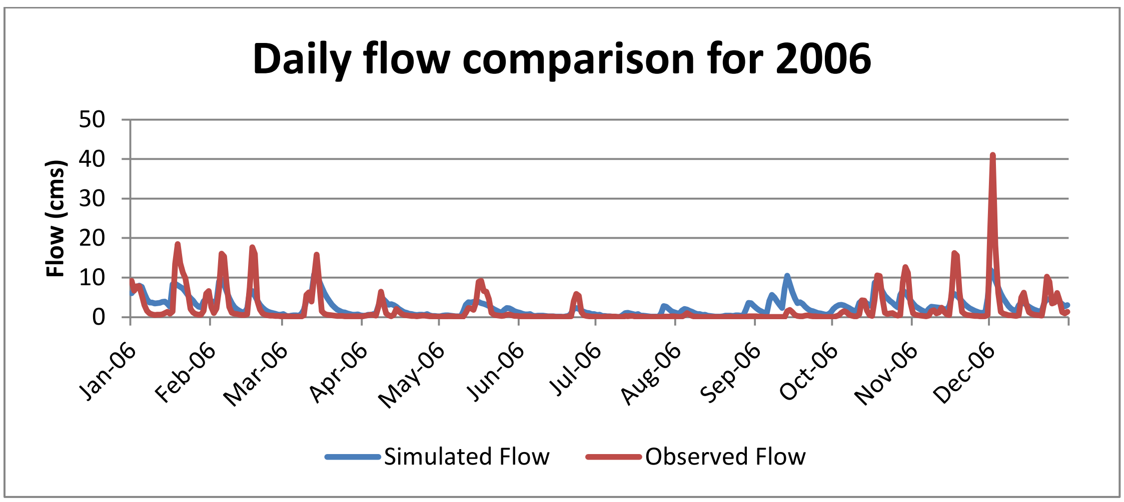

Figure 5. 10: Daily Observed vs Simulated Flow Comparison for 2006

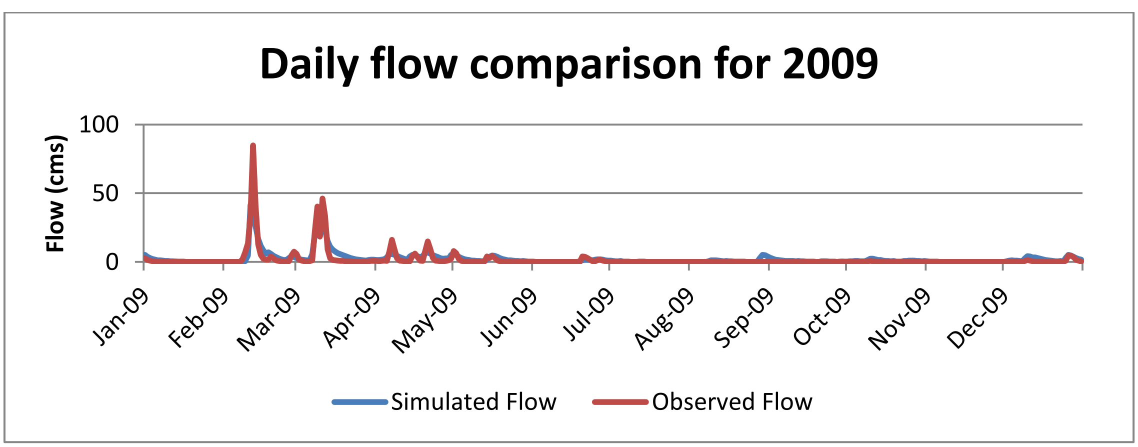

Figure 5. 11: Daily Observed vs Simulated Flow Comparison for 2009

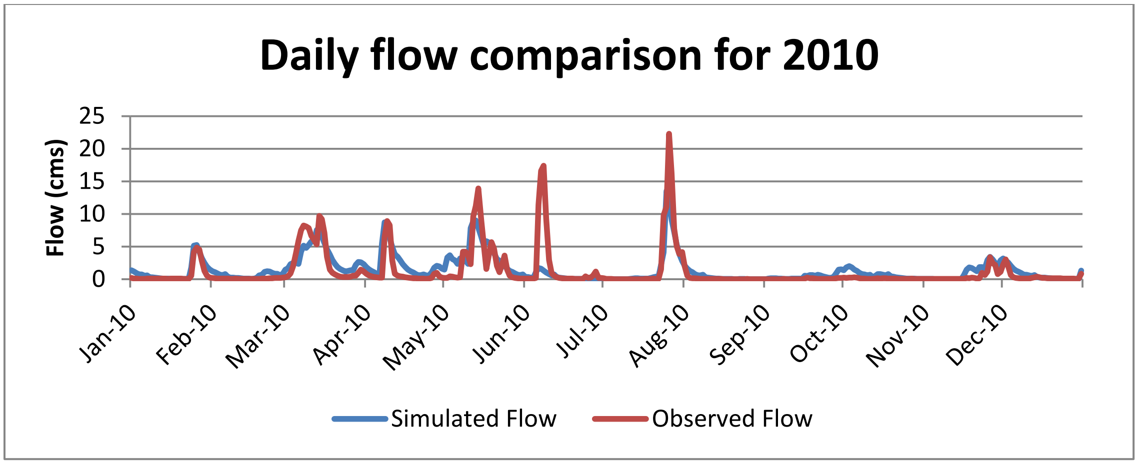

Figure 5. 12: Daily Observed vs Simulated Flow Comparison for 2010

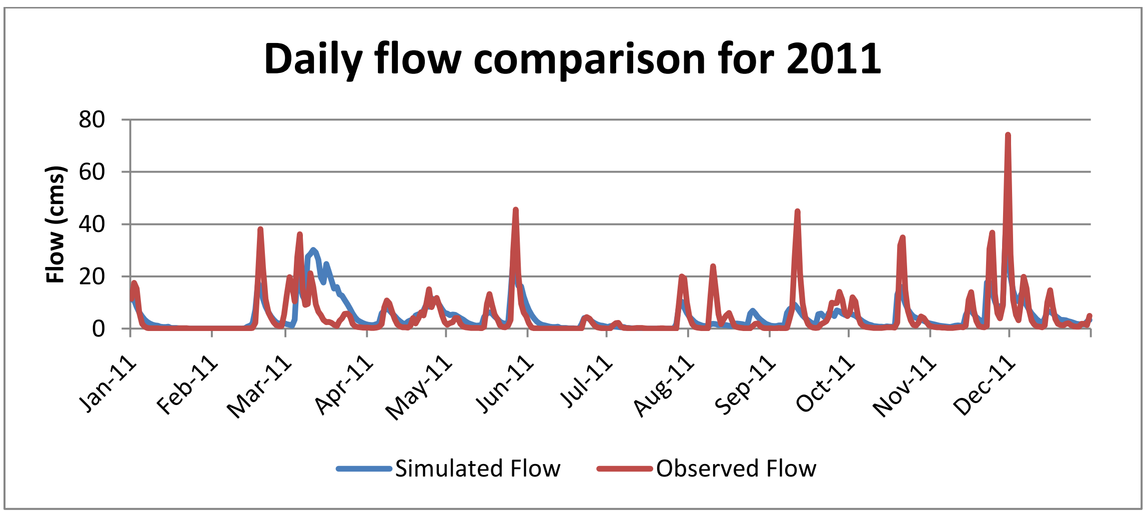

Figure 5. 13: Daily Observed vs Simulated Flow Comparison for 2011

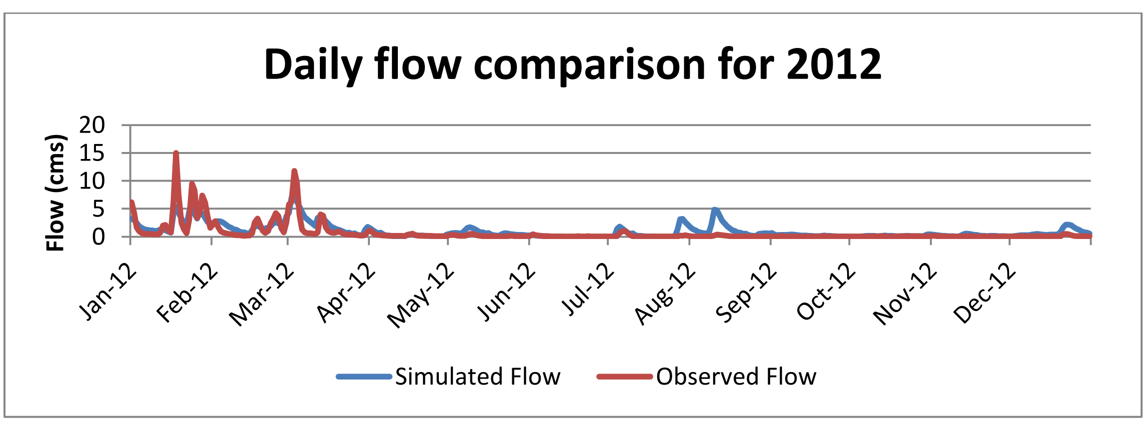

Figure 5. 14: Daily Observed vs Simulated Flow Comparison for 2012

5.2 Water Budget Analysis

The calibrated model results were used for performing water budget analysis on annual, monthly and seasonal basis for time period 2001 to 2012 to determine the basic components of water balance including evapotranspiration, total water yield, surface runoff, tile flow and groundwater flow.

5.2.1 Annual Water Budget

Average annual precipitation for the future simulated period for Canard River Watershed was 911 mm, out of which 586 mm (approximately 65%) was lost as evapotranspiration while the remaining 35% resulted in total water yield constituting surface runoff 226 mm (25%), tile flow 64 mm (7%) and groundwater flow 28 mm (3%) as shown in Figure 5.15 and Table 5.1. High evapotranspiration could be attributed to agricultural predominance and lower groundwater flow resulted from clayey soil type. Higher tile flows as compared to groundwater flows depict the effectiveness of tiles in draining excess water from soil profile. Annual water budget from 2001 till 2012 is presented in Table 5.2.

Table 5. 1: Average Annual Water Budget

Precipitation (mm)	911
Evapotranspiration (mm)	586
Total Water Yield (mm)	301
Total Aquifer Recharge (mm)	28
Surface Runoff (mm)	226
Tile Flow (mm)	64
Groundwater (mm)	11
Revap (mm)	2

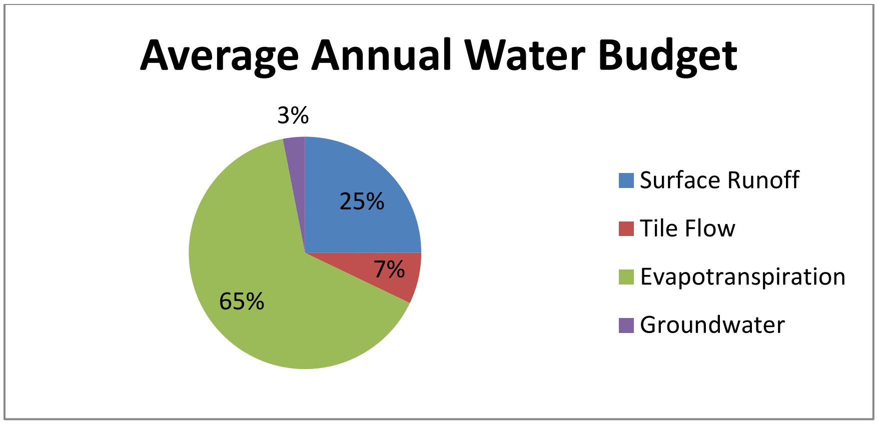

Figure 5. 15: Average Annual Water Balance

Table 5. 2: Annual Water Budget from 2001 to 2012

Year	Precipitation (mm)	Evapo-transpiration (mm)	Total Water Yield (mm)	Surface Runoff (mm)	Tile Flow (mm)	Groundwater (mm)
2001	751.89	443.79	313.07	240.38	70.80	23.61
2002	699.36	380.09	283.62	198.07	89.71	28.54
2003	928.63	473.35	407.11	301.94	97.82	33.32
2004	886.33	493.42	352.79	227.84	126.85	38.70
2005	721.03	385.35	298.13	246.60	47.86	21.58
2006	1061.92	543.20	487.95	289.76	191.29	55.05
2007	789.93	439.05	299.04	240.15	56.25	19.85
2008	953.56	496.82	437.89	367.29	72.17	27.03
2009	853.44	452.58	398.08	316.21	76.55	29.55
2010	791.49	466.49	262.82	199.21	67.72	24.19
2011	1477.30	540.57	887.92	643.97	234.47	73.54
2012	643.56	462.56	175.65	120.91	52.03	17.25

5.2.2 Average Monthly Water Budget

Average monthly water budget analysis as shown in Figure 5.16 was performed to find out the variation of different hydrological components throughout the year. The average monthly water budget values for each component are presented in Appendix Table A-3. It was observed that surface runoff was the lowest in summer (August) due to increased loss of water by evapotranspiration. Then it kept on increasing till winter (February) wherefrom it again started declining. Baseflow and water yield also followed similar pattern with the lowest in summer (August), then they increased till winter (March), after that again started declining. Evapotranspiration peaked during summer (July) due to elevated temperatures, solar radiation and agricultural growth, and then started declining till winter (January), after that it started rising again. Baseflow peak followed surface runoff peak and it can be attributed to ground water lag time.

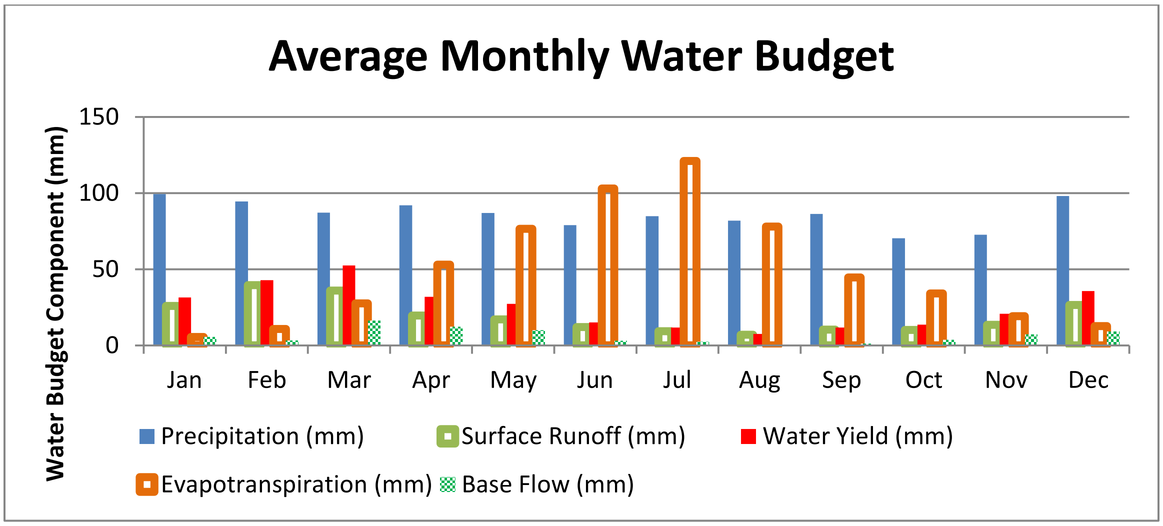

Figure 5. 16: Average Monthly Water Budget Analysis

5.2.3 Seasonal Water Budget

Seasonal water budget analysis was performed based on winter (January, February, March and December), spring (April and May), summer (June, July, August and September) and fall (October and November). Average values and percentages are presented in Table 5.3 and plot is shown in Figure 5.17. The water budget analysis for each season is presented in Appendix Tables A-4, A-5, A-6 and A-7. The maximum evapotranspiration occurred in summer (46% of annual evapotranspiration), while the lowest in winter (5% of annual evapotranspiration). The highest surface runoff was found occurring in winter (40% of annual surface runoff) while the lowest in summer (16% of annual surface runoff). Significant tile flow (46% of annual tile flow) and baseflow (47% of annual baseflow) occurred in spring while least baseflow (2% of annual baseflow) and tile flow (2% of annual tile flow) occurred in summer. The highest groundwater flow and tile flow in spring suggest snow melt is the main process leading to sub-surface flows. Surface runoff and evapotranspiration bear negative co-relation. They being the dominant processes, evapotranspiration is the major process dominating water loss during warm summer period, while the surface runoff dominating during colder winter periods.

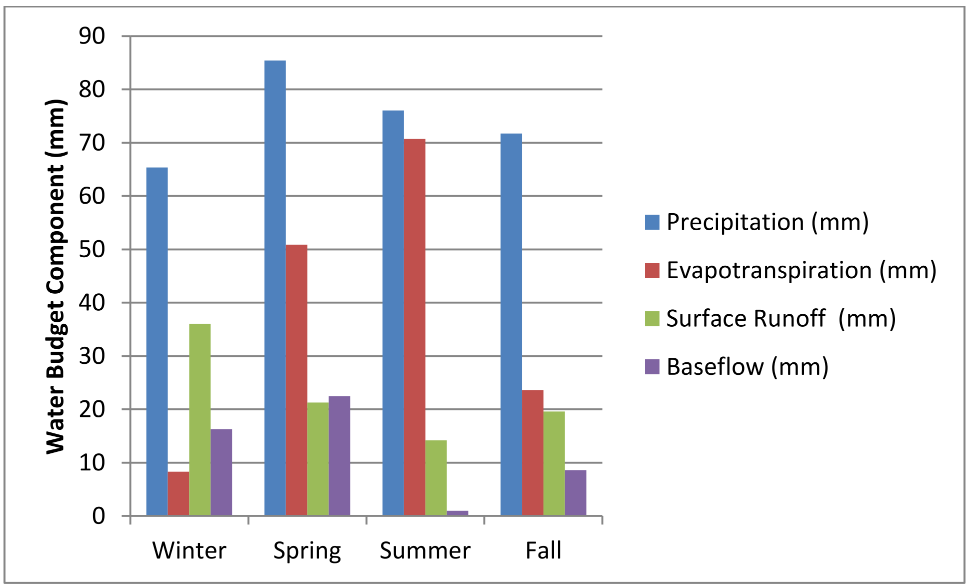

Figure 5. 17: Seasonal Water Budget

Table 5. 3: Seasonal Water Budget

Season	Precipitation (mm) %	Evapo-transpiration (mm) %	Total Water Yield (mm) %	Surface Runoff (mm) %	Groundwater (mm) %	Tile Flow (mm) %
Winter	65.34 (22)	8.29 (5)	49.02 (38)	36.07 (40)	4.22 (36)	12.09 (33)
Spring	85.42 (29)	50.86 (33)	38.63 (30)	21.26 (23)	5.53 (47)	16.91 (46)
Summer	76.05 (25)	70.67 (46)	15.08 (12)	14.18 (16)	0.25 (2)	0.73 (2)
Fall	71.73 (24)	23.61 (15)	25.01 (20)	19.58 (21)	1.87 (16)	6.76 (19)

Note: Water budget component values in mm are presented in Table 5.3, while percentages are given within parentheses.

5.2.4 Sub-watershed Based Water Budget Analysis

Precipitation

Precipitation in the Canard River Watershed during the period 2001 to 2013 ranged between 858 mm to 973 mm as in Figure 5.18. The maximum precipitation was observed in the northern part of Canard River Watershed, which is closer to Windsor Airport Climate Monitoring Station followed by south western side which is closer to Amherstburg Climate Monitoring Station. The eastern half of watershed which is closer to Harrow Climate Monitoring Station received the lowest rainfall. Most of the area contributing to Lukerville streamflow monitoring station received the least precipitation.

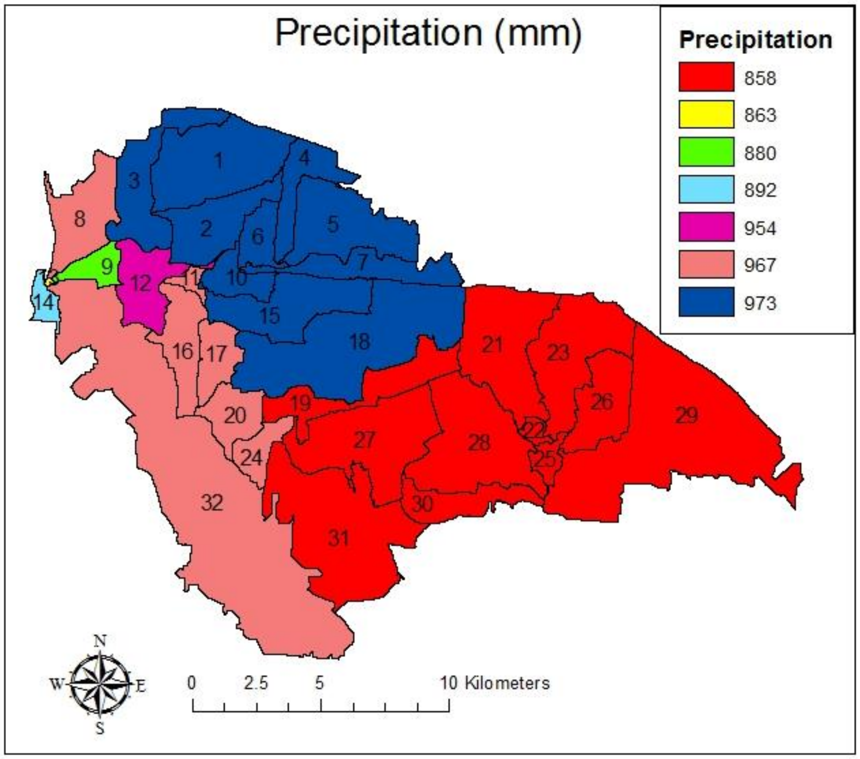

Figure 5. 18: Precipitation Distribution in Canard River Watershed

Evapotranspiration

Evapotranspiration distribution in different sub-watersheds is presented in Figure 5.19. The evapotranspiration values range between 407 and 543 mm in the Canard River Watershed. The maximum evapotranspiration occurred in sub-watersheds 11 and 24 which lie in the central areas of the watershed while the least evapotranspiration occurred in sub-watershed 14 which lies on the western side of watershed. Major portion of the watershed experienced evapotranspiration between 438 and 476 mm.

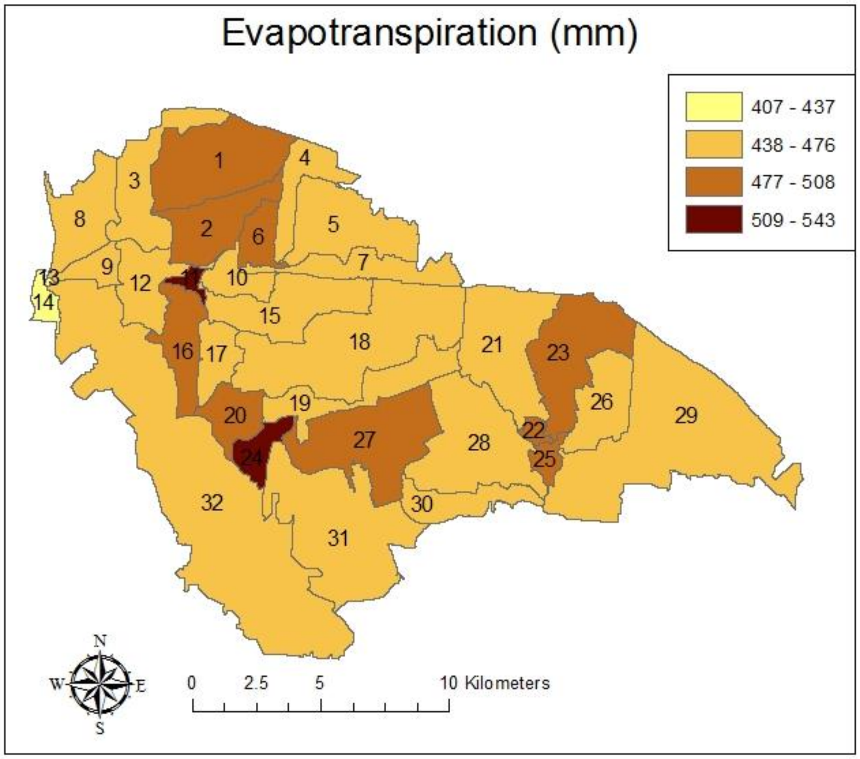

Figure 5. 19: Evapotranspiration Distribution in Canard River Watershed

Water Yield

The water yield in SWAT modeling refers to the streamflow in the general parlance of hydrology. The water yield distribution in the Canard River watershed is presented in Figure 5.20. Water yield values for entire watershed ranged between 292 and 516 mm. Maximum water yield occurred in north western and south western side of watershed, while south eastern side observed the least water yield. This distribution followed a pattern similar to that of the precipitation as can be seen in Figure 5.18. Thus the higher water yield was predicted in the sub-watersheds receiving higher precipitation.

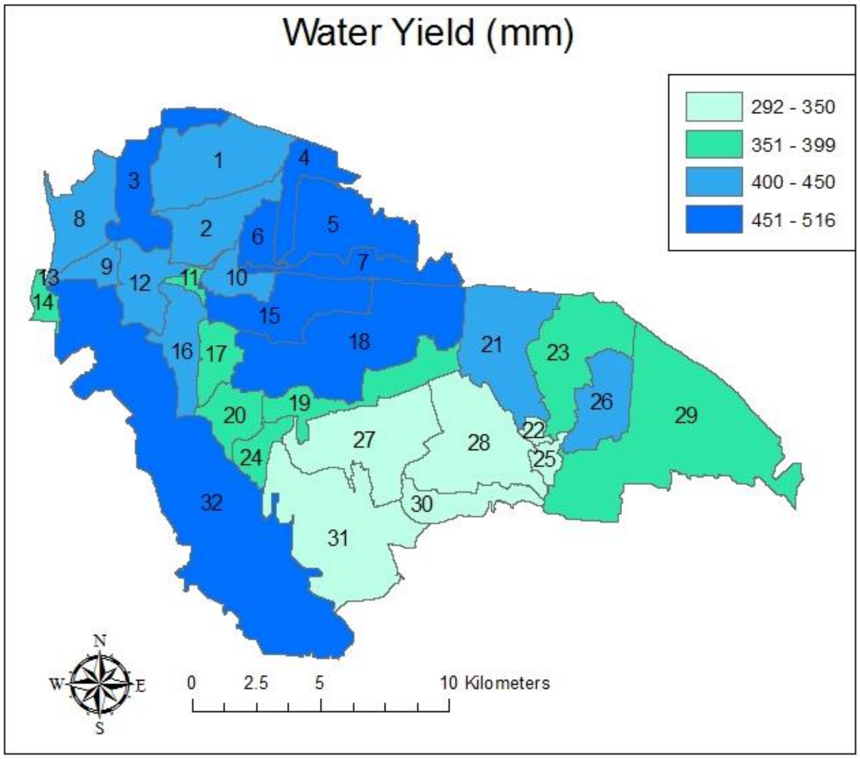

Figure 5. 20: Water Yield Distribution in Canard River Watershed

Surface Runoff

The surface runoff distribution in the Canard River watershed is presented in Figure 5.21. Surface runoff in entire watershed varied between 223 – 349 mm. From Figure 5.21 it is evident that maximum surface runoff occurred in the northern part of the watershed followed by western side of the watershed while the eastern side observed least surface runoff. As the watershed has mostly flat topography with gentle slope thus precipitation distribution played a significant role in runoff contribution from different sub-watersheds. The sub-watersheds receiving higher precipitation projected higher surface runoff while the areas receiving lower precipitation resulted in lower surface runoff. These results corroborate with water yield and precipitation results discussed in previous sections.

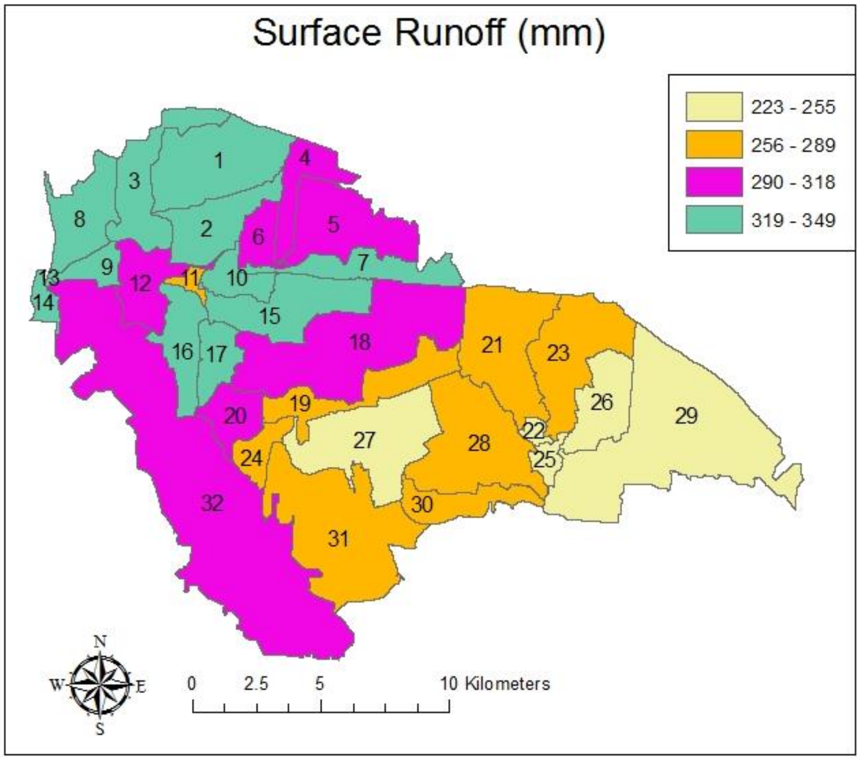

Figure 5. 21: Surface Runoff Distribution in Canard River Watershed

5.3 Sediment Analysis

5.3.1 Observed Sediment Data Analysis

The observed sediment concentration data for Lukerville station was used for performing sediment analysis. About 32 samples were collected from 1989 till 2003 during different months and different flow conditions. These samples were divided into four seasons and further they were divided into two categories within each season based on whether they were collected during peak flow or baseflow conditions. The analysis is discussed in the following section.

Winter:

Five observed samples were collected in winter season of which two samples were taken during peak flow while three during baseflow. Higher sediment concentration was observed during peak flow (1021 and 409 mg/l) while lower concentrations were observed during baseflow (57, 22, 21 mg/l).

Spring:

There were ten observed samples collected in spring. Out of them, six samples were collected during peak flows while remaining four samples were taken during baseflow. Higher sediment concentration was observed during peak flows (492, 354, 254, 229, 205 and 181 mg/l), while lower concentrations were observed during baseflow (79, 88, 71 and 75 mg/l).

Summer:

During summer twelve samples were collected, out of which three samples were taken during peak flow, six samples were collected during mixed flow conditions while three during baseflow conditions. Higher concentrations were observed during peak flow (177, 134 and 225 mg/l). Intermediate range of concentrations were observed during mixed flow (52, 80, 22, 65, 132 and 173 mg/l), while low concentrations were observed during baseflow (55, 41 and 15 mg/l).

Fall:

Five samples were collected in fall of which two samples were taken during peak flow while three during baseflow. Higher sediment concentration was observed during peak flow (333 and 86 mg/l) while lower concentrations were observed during baseflow (66, 43 and 23 mg/l).

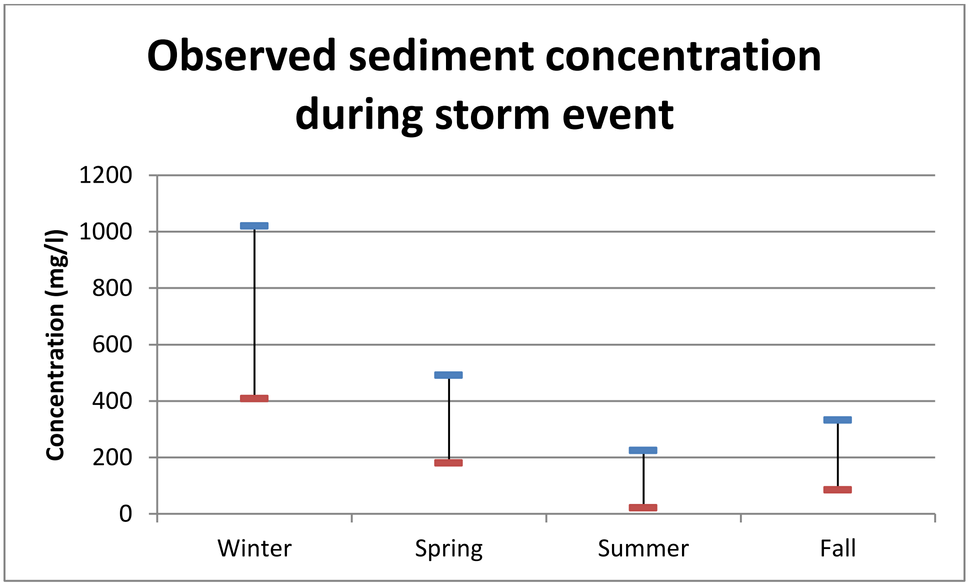

Figure 5. 22: Observed sediment concentration range during storm event

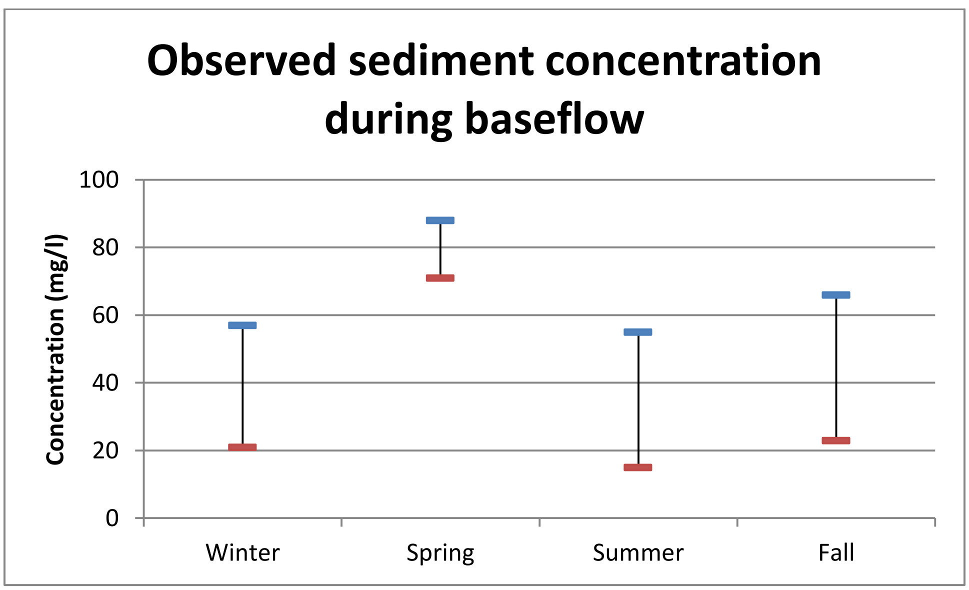

Figure 5. 23: Observed sediment concentration range during baseflow

Out of four seasons, the highest concentrations were observed during winter followed by spring due to barren land and loosened soil due to freeze thaw cycle while lower concentrations were observed during summer and fall due to crop cover as shown in Figure 5.22. Observed sediment concentration range during storm event and baseflow are shown in Figure 5.22 and Figure 5.23 respectively. Higher concentrations were observed during storm event as compared to baseflow which could be attributed to higher erosion on land surface and river bed. Highest concentration during baseflow was observed in spring.

5.3.2 Seasonal Range Comparison:

Due to limited observed data (32 samples), the sediment concentration and loading analysis was restricted to seasonal time scale. The observed data was divided into four sub-groups corresponding to each season. The maximum and minimum sediment concentrations during storm event and baseflow for each season were selected to check the range of simulated sediment concentration as shown in Figure 5.24 and Figure 5.25 respectively.

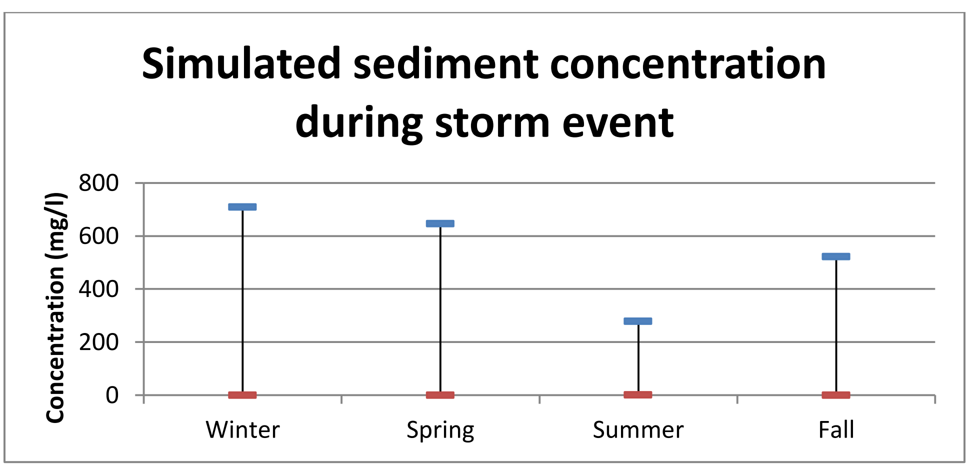

Figure 5. 24: Simulated sediment concentration range during storm event

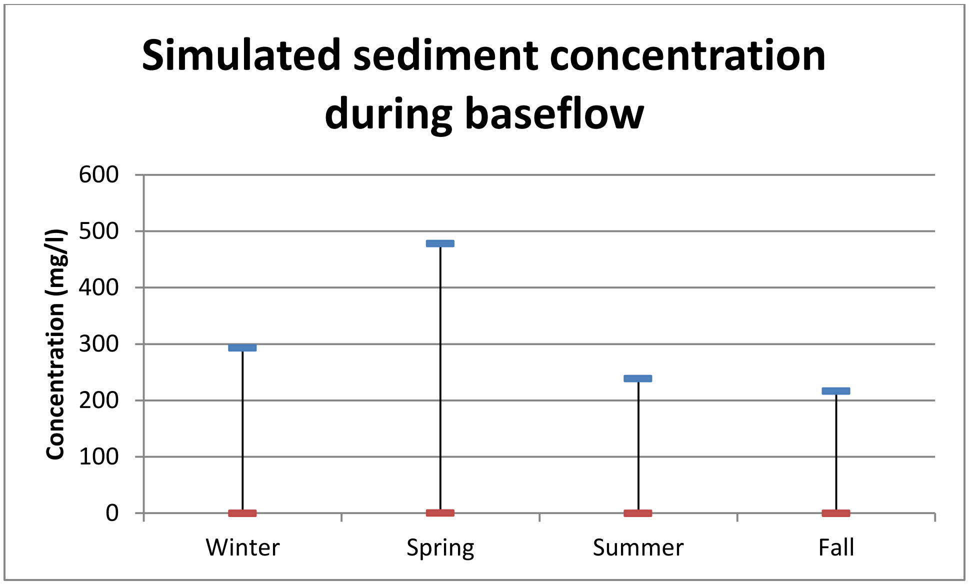

Figure 5. 25: Simulated sediment concentration range during baseflow

Highest sediment concentration during storm event was found in winter followed by spring, fall and summer as shown in Figure 5.24. Highest concentration during baseflow was found in spring as shown in Figure 5.25. These results corroborate with observed sediment results.

Winter:

The model simulated maximum sediment concentration ranged between 308 and 710 mg/l, whereas minimum sediment concentration ranged between 0 and 0.93 mg/l for years 2001 to 2012 as shown in Figure 5.26. The average sediment concentration ranged between 38.5 and 90.8 mg/l for same time period. The sediment concentration in the observed samples ranged between 21 and 1021 mg/l for winter. Thus the maximum simulated sediment concentration for winter period lies between the observed values during peak flow i.e., 409 and 1021 mg/l. The average simulated concentrations lie between minimum and maximum observed concentrations, thus ensuring that credibility of simulated values. The sediment loading lies between 12.48 and 123.9 ton/day as shown in Figure 5.27. The maximum average loading of 124 ton/day occurred in 2011 due to extreme precipitation in that year.

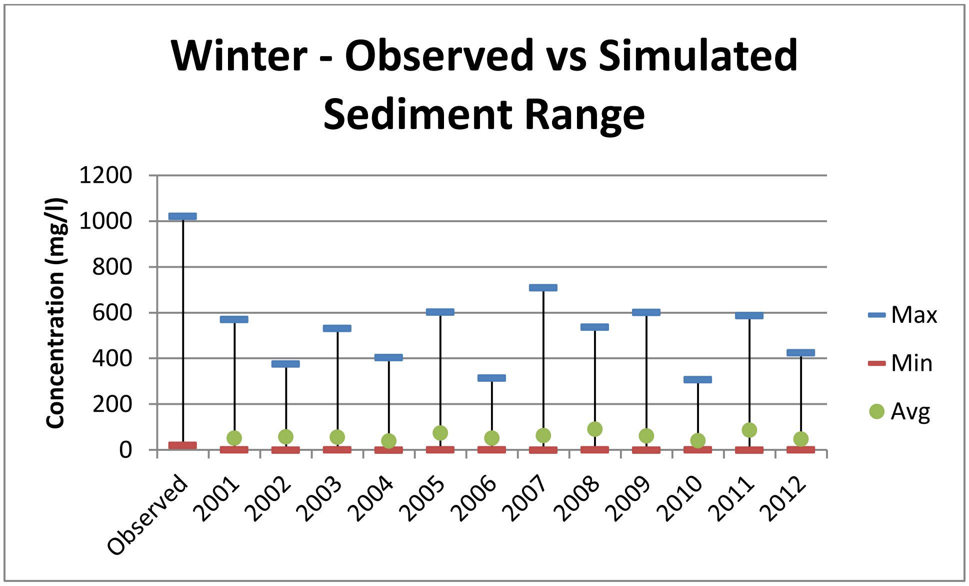

Figure 5. 26: Comparision of Observed and Simulated Sediment Concentration Range during Winter

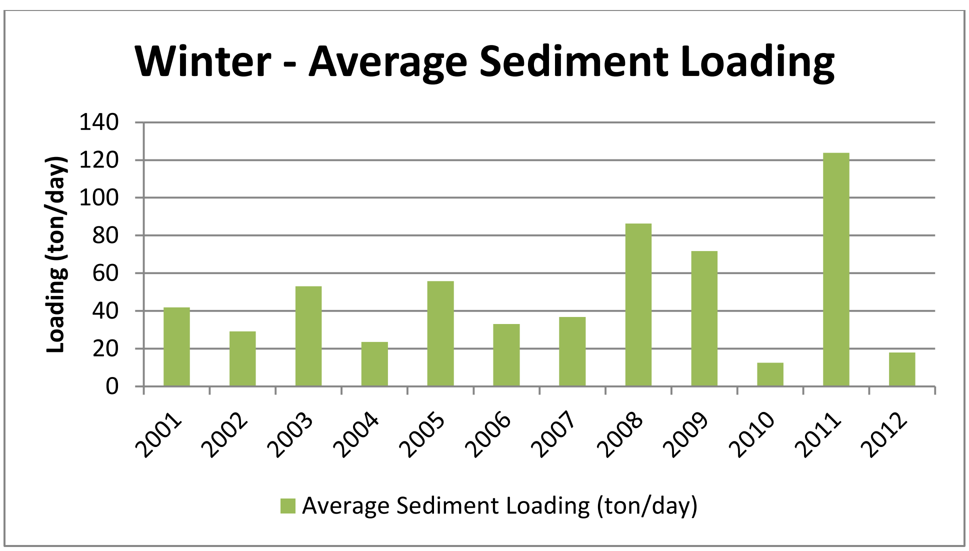

Figure 5. 27: Average Sediment Loading during Winter

Spring:

The observed sediment concentration for spring lies between 71 and 492 mg/l. The model simulated results for the period 2001 to 2012 showed maximum sediment concentration lie between 198 and 648 mg/l, whereas minimum sediment concentration vary between 0.25 and 4.9 mg/l as shown in Figure 5.28. The average sediment concentration ranged between 24 and 86 mg/l for same time period. The maximum simulated sediment concentration for spring lie between the observed values corresponding to peak flow concentrations, i.e., 181 and 492 mg/l except in 2011 when the concentration value of 648 mg/l was found (2011 received exceptionally high precipitation). Except for 2002 and 2011 the average simulated concentrations (76 and 86 mg/l, respectively) other values lie below minimum observed concentrations. The spring average sediment concentration range (24 - 86 mg/l) is slightly lower than winter average sediment concentration range (91 – 39 mg/l), which corroborate with observed ranges. The average sediment loading lies between 3.7 and 95.7 ton/day as shown in Figure 5.29. The maximum average loading of 95.7 tonnes/day occurred in 2011 due to extreme precipitation in that year.

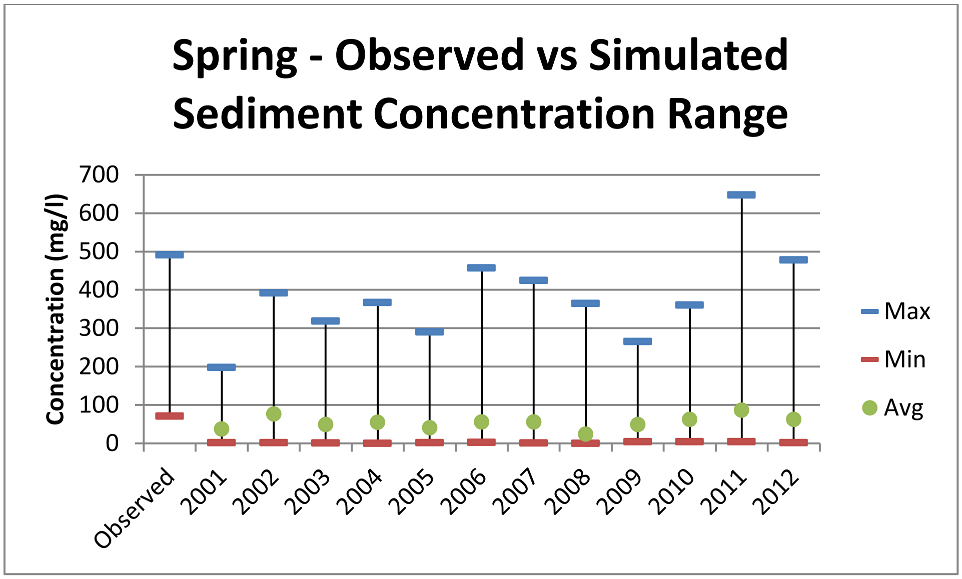

Figure 5. 28: Comparision of Observed and Simulated Sediment Concentration Range during Winter

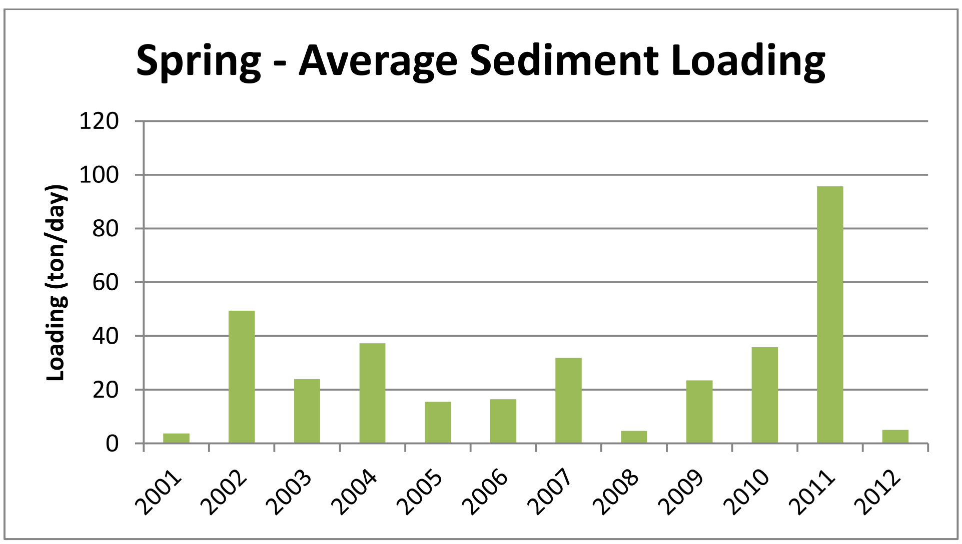

Figure 5. 29: Average Sediment Loading during Spring

Summer:

The concentration of 12 observed sediment samples collected in summer lie between 15 to 225 mg/l. The model simulated maximum sediment concentration lie between 128 and

279 mg/l, whereas minimum sediment concentration vary between 0 and 1.9 mg/l as shown in Figure 5.30. The average sediment concentration ranged between 15 to 33 mg/l. The maximum simulated sediment concentrations for years 2003, 2004, 2006 - 2008 lie above the observed values during peak flow i.e. 22 and 225 mg/l, while for other years the values lie within the observed range. Average simulated concentrations lie between maximum and minimum observed concentration range. The summer average sediment concentration range (15 – 32 mg/l) is significantly lower than that of spring (24 - 86 mg/l) and winter (91 – 39 mg/l), similar pattern is followed in observed ranges. The average sediment loading lies between 0.7 and 16 ton/day as shown in Figure 5.31.

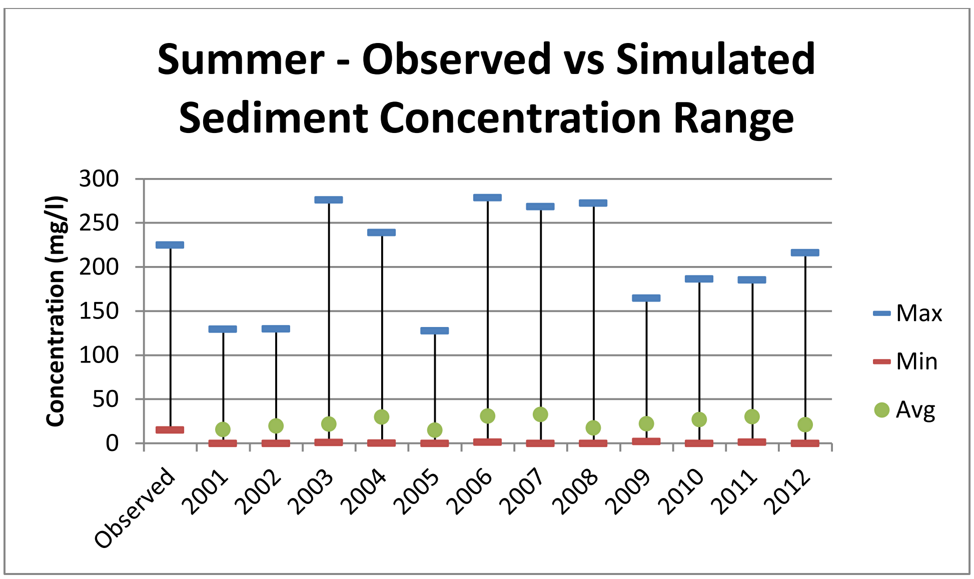

Figure 5. 30: Comparision of Observed and Simulated Concentration Sediment Range during Summer

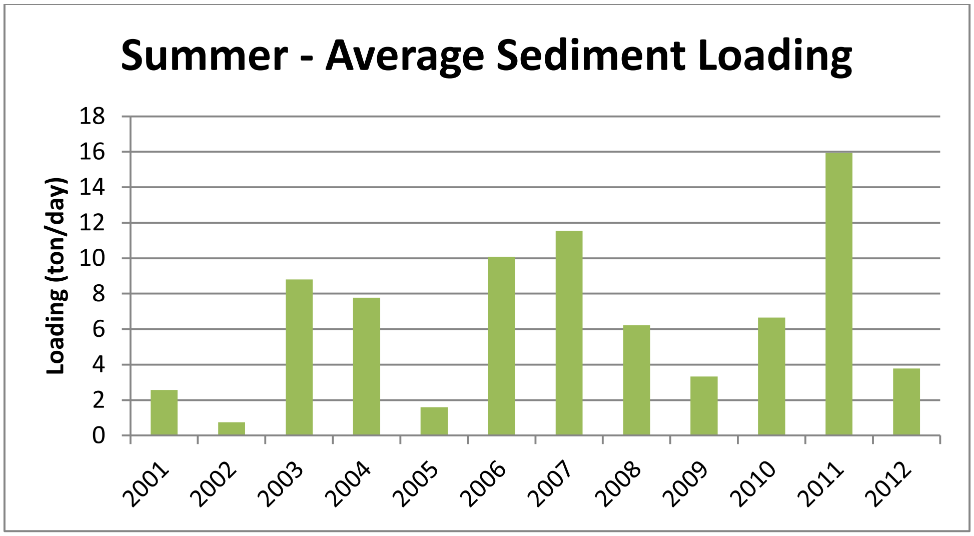

Figure 5. 31: Average Sediment Loading during Summer

Fall:

The concentration of five observed sediment samples collected during fall lie between 23 and 333 mg/l. The model simulated maximum sediment concentration lie between 124 and 524 mg/l, whereas the minimum sediment concentration vary between 0.05 and 1.7 mg/l as shown in Figure 5.32. The average sediment concentration ranged between 17 to 55 mg/l. The maximum simulated sediment concentrations lie below the observed maximum values during peak flow of 333 mg/l, except for 2011 due to heavy precipitation. Average simulated concentrations lie between maximum and minimum observed concentration range, except for 2009 (17 mg/l). The average sediment concentration range during fall (17 – 55 mg/l) is significantly lower than that of spring (24 - 86 mg/l) and winter (39 - 91 mg/l) but higher than summer (15 – 32 mg/l); similar pattern existed in observed ranges. The average sediment loadings lie between 0.9 and 22 ton/day, except for 2011 (85 tonnes/day) as shown in Figure 5.33.

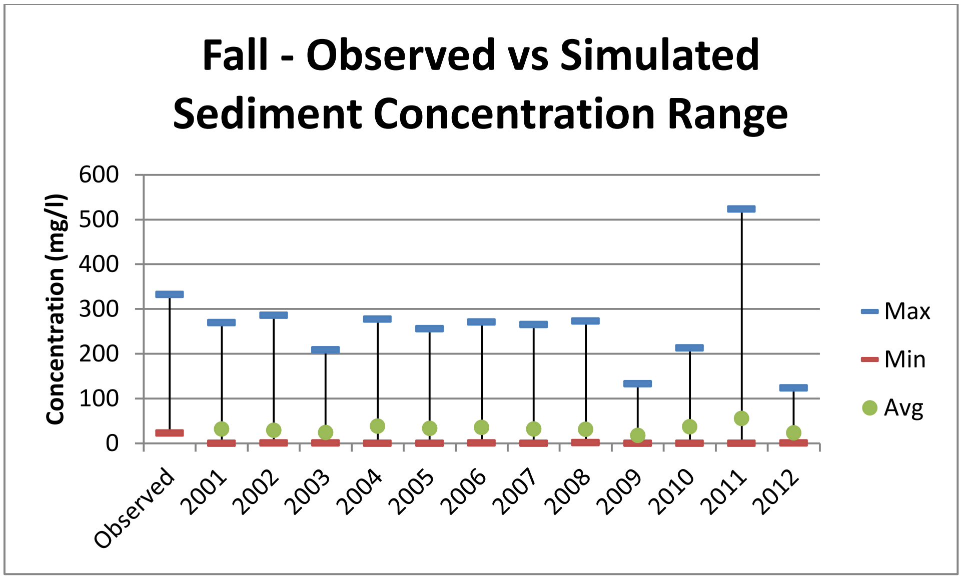

Figure 5. 32: Comparision of Observed and Simulated Concentration Sediment Range during Fall

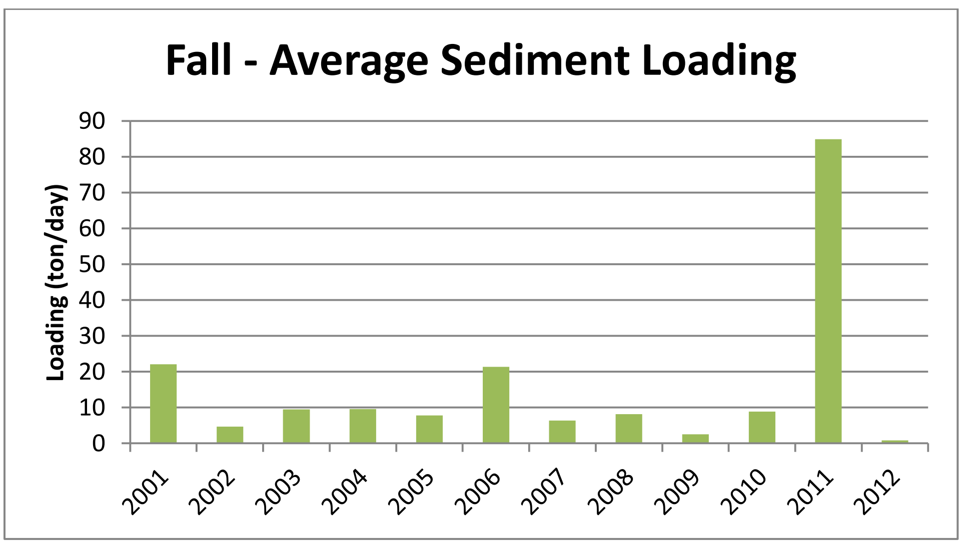

Figure 5. 33: Average Sediment Loading during Fall

5.3.3 Average Annual Sediment Loading Trends

The average annual sediment range lies between 8 and 77 tonnes/day. The maximum and minimum sediment loading occurred in 2011 and 2012, respectively as shown in Figure

5.34. The highest loading in 2011 was due to excess precipitation in this year as compared to other years.

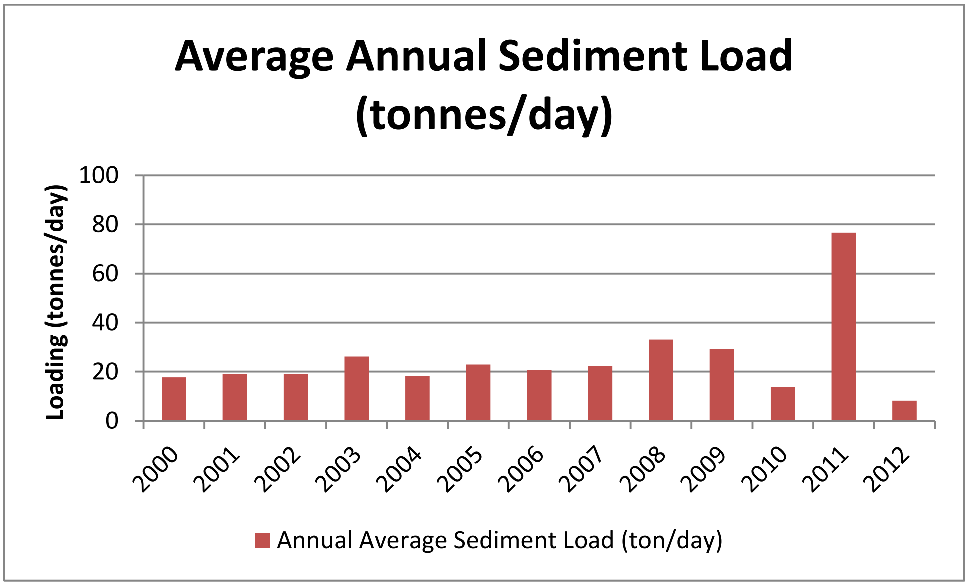

Figure 5. 34: Average Annual Sediment Load (ton/day)

5.3.4 Seasonal Sediment Loading

Winter season observed maximum loading in almost all years followed by spring, fall and summer as shown in Figure 5.35. Maximum loading rate in winter could be attributed to barren land, repeated soil freeze and thaw cycles due to sub-zero temperatures, increased surface runoff and decreased evapotranspiration. Spring loading occurs mainly due to snow melt and surface runoff events, but rising temperature and onset of vegetative cover increase evapotranspiration. Higher baseflow in spring as compared to winter could also be another reason for reduction of sediment loading as compared to winter. Vegetative cover during summer causes excessive water loss due to evapotranspiration and reduces soil erosion. It results in reduced sediment loadings due to reduced surface runoff. The carrying capacity of surface runoff also reduces. Fall again noticed increased sediment loading due to loosing vegetation.

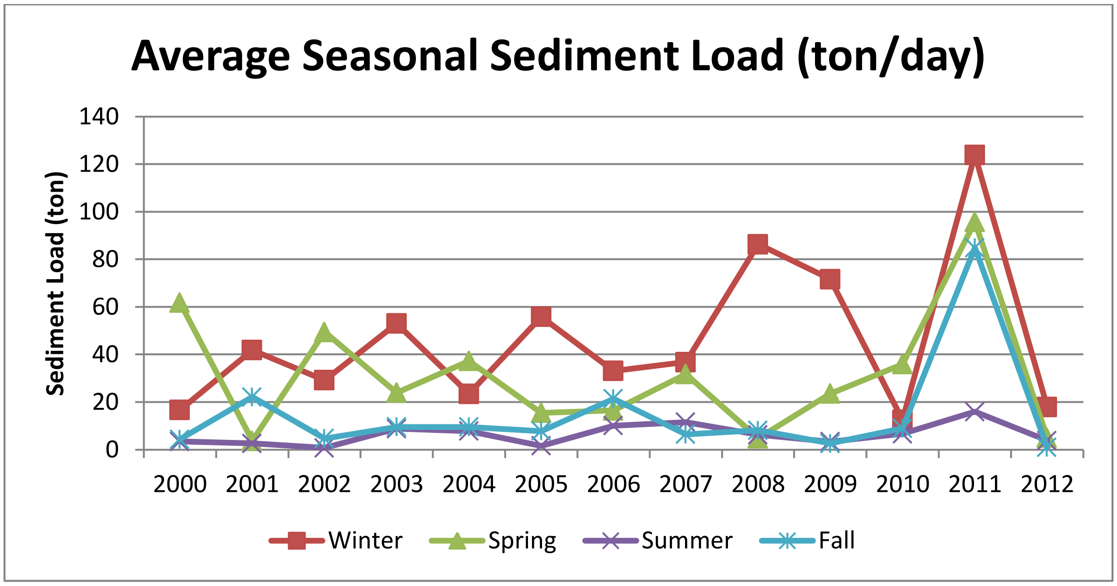

Figure 5. 35: Average Seasonal Sediment Load (ton/day)

5.3.5 Flow vs Sediment Comparison

Daily flow was compared with daily sediment loading in Figure 5.36. It was observed that peak loading occurred during peak flows at the beginning and end of year (winter period). While during middle of year (summer) lower flows and reduced loadings were observed. The higher sediment concentrations were also observed during peak flows and on the other hand the lower sediment concentrations were observed during baseflow periods as shown in Figure 5.37. This analysis indicates that the higher soil erosion takes place during peak flow and baseflow contribution is insignificant. Thus the effort should be made to reduce peaks for reducing sediment loss.

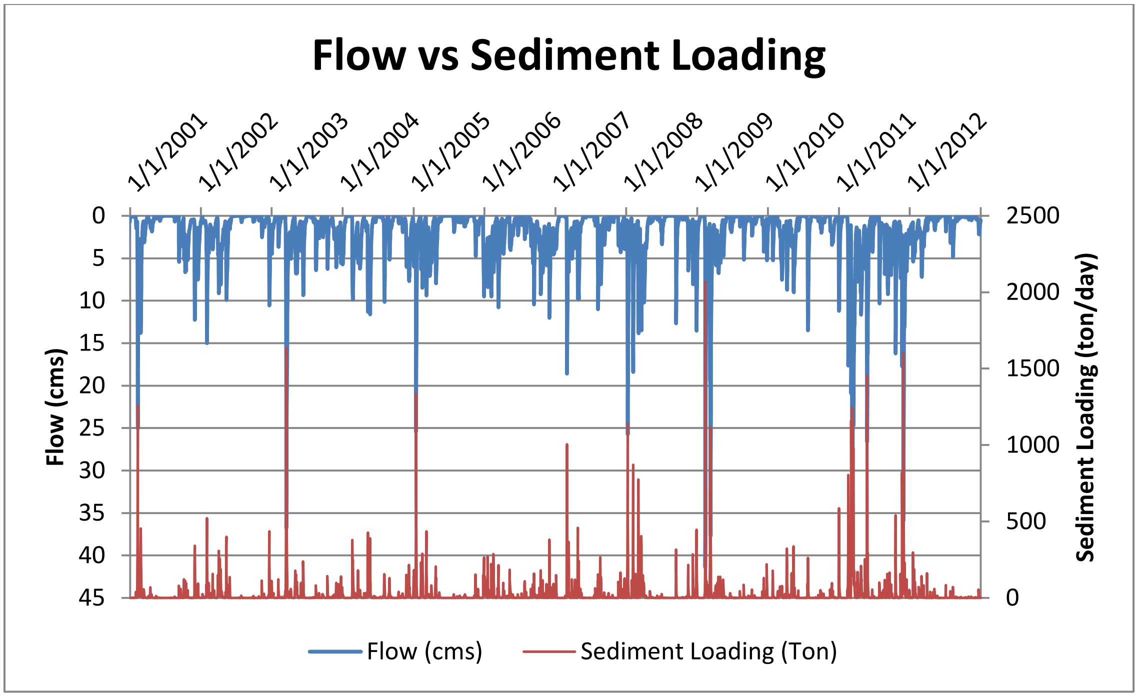

Figure 5. 36: Flow vs Sediment Loading

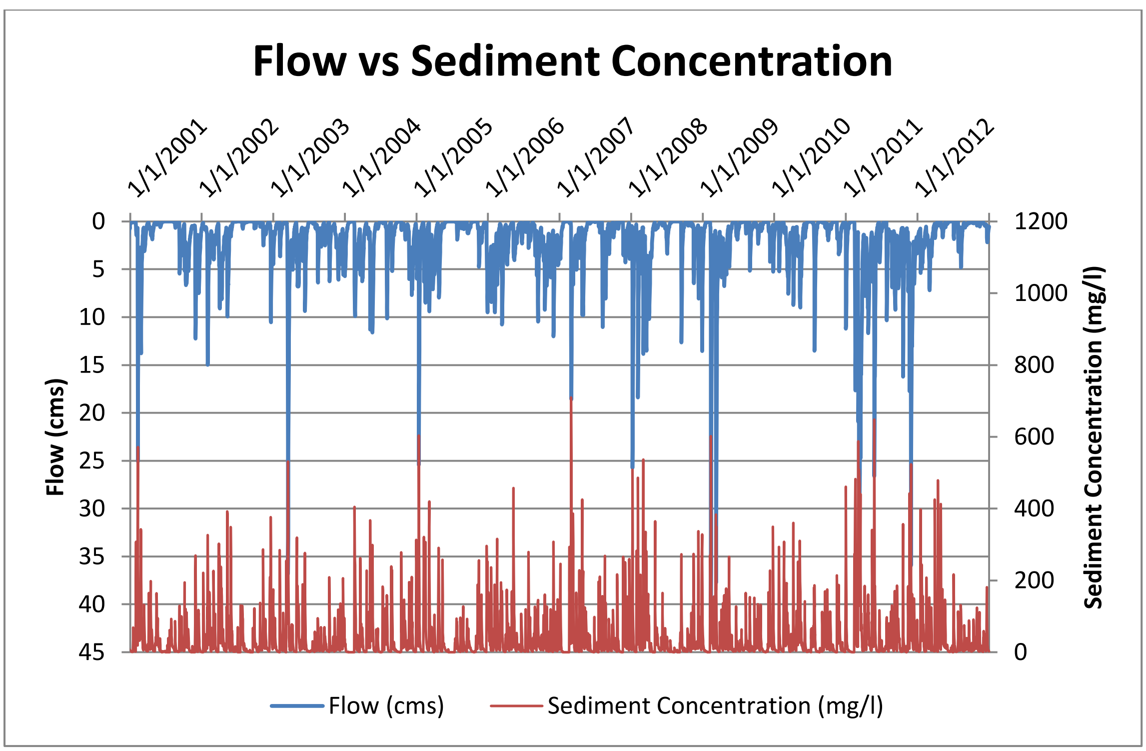

Figure 5. 37: Flow vs Sediment Concentration

5.3.6 Monthly Average Loading

Average monthly sediment loading vs surface runoff plot shown in Figure 5.38 depicts strong correlation between them. Also maximum loading takes place during February and the lowest during August. Both surface runoff and sediment loading kept on decreasing from February until they reached the lowest in August, then started rising again until they reached maximum in February.

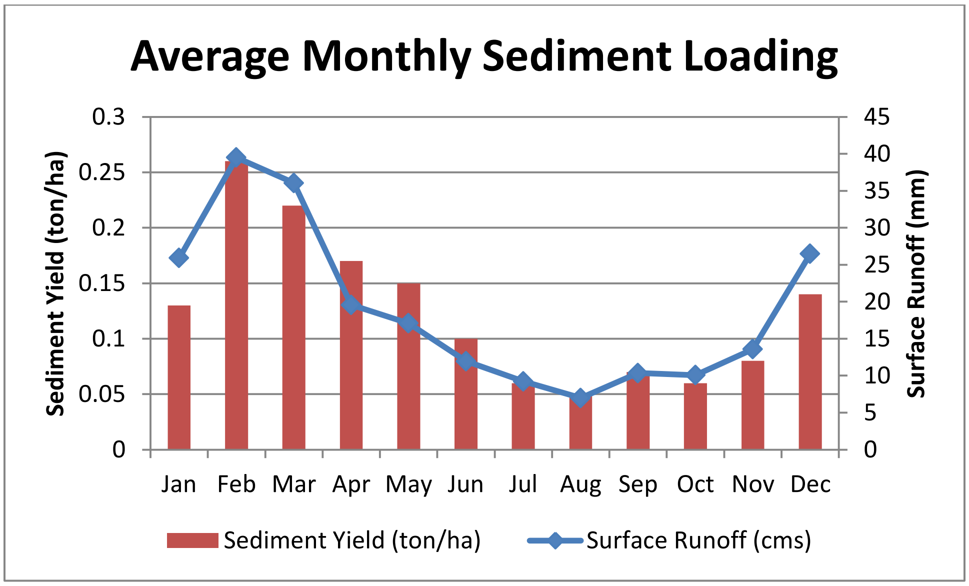

Figure 5. 38: Average Monthly Sediment Loading

5.3.7 Sediment Yield

The sediment yield analysis was performed for 32 sub-watersheds and its distribution is shown in Figure 5.39. The sediment yield lied between 0.18 and 6.3 ton/ha. Sub-watershed number 7 was found to contribute maximum towards sediment loading (6.3 ton/ha), while sub-watershed 25 contributed minimum towards sediment loading (0.18 ton/ha). Average contribution was found out to be 2 ton/ha. Maximum soil erosion occurred in northern part of watershed due to higher precipitation and surface runoff as discussed in the previous sections. The southern half of the watershed contributed least towards the sediment loading.

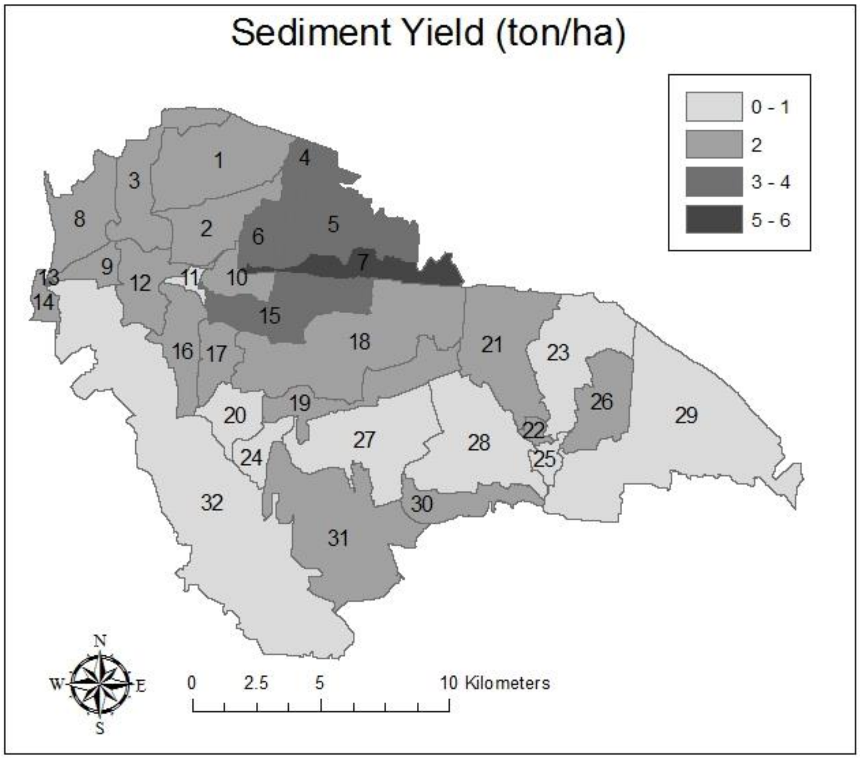

Figure 5. 39: Sediment Yield in Canard River Watershed

5.4 Microbial Analysis

5.4.1 Daily Concentration of *E. coli*

Daily *E. coli* concentrations obtained from the SWAT model simulations were analyzed for the period 2008 – 2012 as shown in Figure 5.40. The daily *E. coli* concentration values range between 0 – 678800 CFU/100ml while the average was 4424 CFU/100ml. Due to a huge variation in the range, the concentrations were converted from linear scale to log scale for better representation. In log scale the range was 0.75 to 5.83 while the average was 2.84.

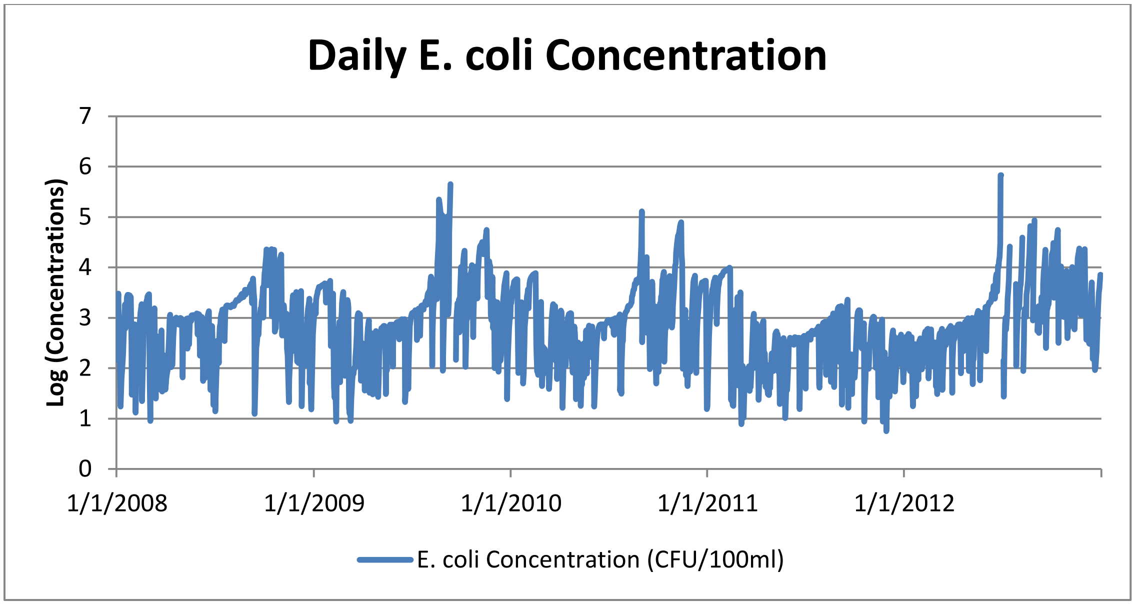

Figure 5. 40: Daily *E. coli* concentraion

5.4.2 Average Annual *E. coli* Loading

Average annual E. coli loading is presented in Figure 5.41. Daily loading from 2001 to 2013 was calculated by using daily flows and *E. coli* concentration and average loading for each year was calculated to determine the trend. The annual average values lied between 4,020,486 – 8,108,321 CFU/day and average was 5,857,610 CFU/day. It was found that on an average the *E. coli* loading increased over the span of thirteen years.

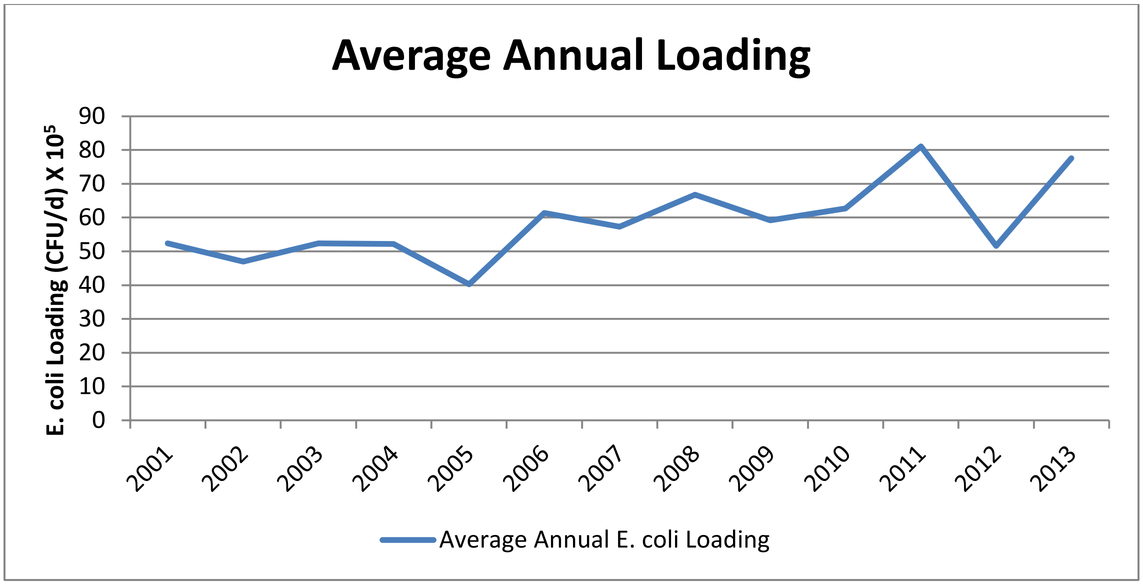

Figure 5. 41: Average Annual *E. coli* Loading

5.4.3 Seasonal *E. coli* Analysis

Monthly average concentrations for winter, spring, summer and fall are shown in Figures 5.42, 5.43, 5.44 and 5.45 respectively. It was observed that the higher concentrations occurred in winter and fall while spring and summer had lower concentrations. The average monthly values for *E. coli* concentration are presented in Appendix Table A–10.

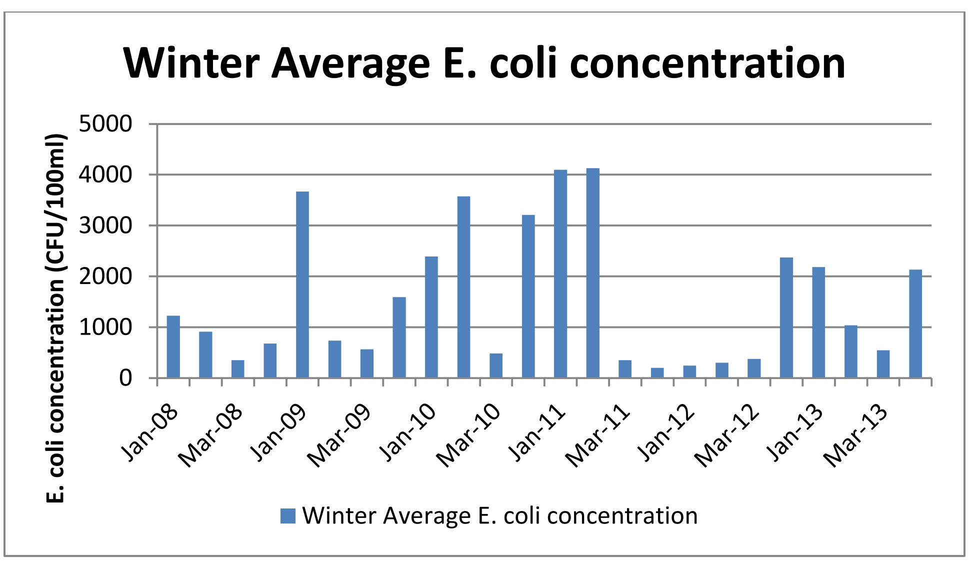

Figure 5. 42: Average *E. coli* concentration during Winter

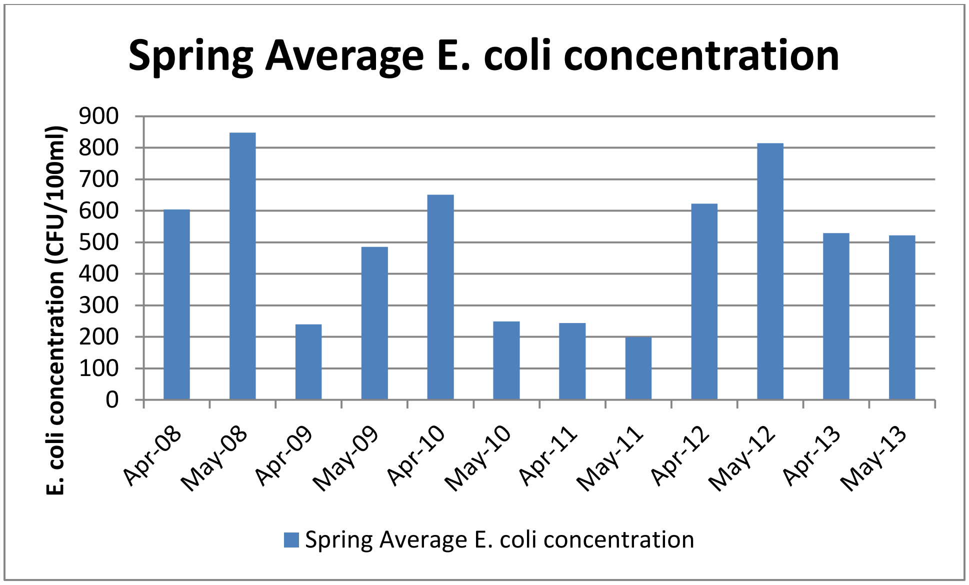

Figure 5. 43: Average *E. coli* concentration during Spring

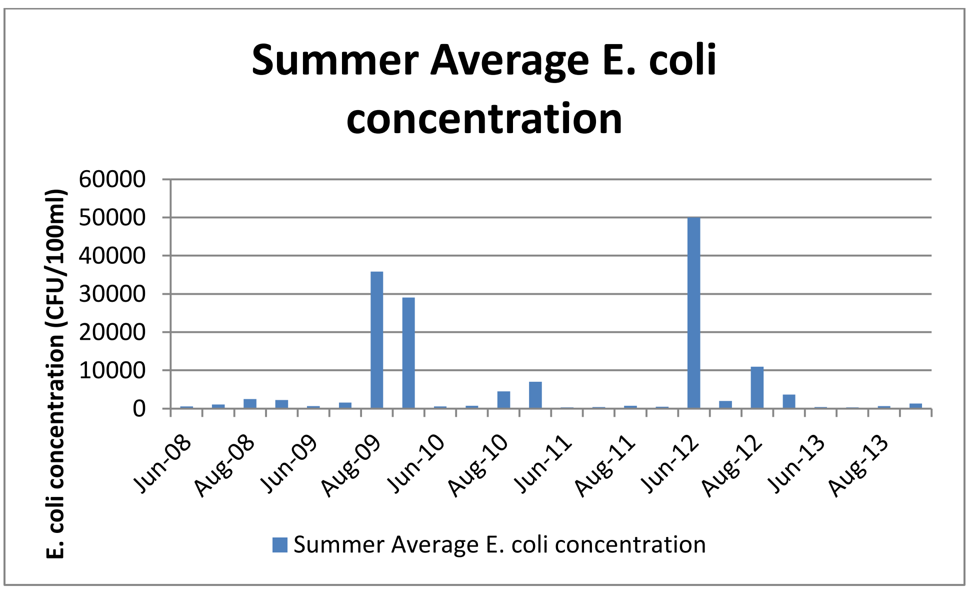

Figure 5. 44: Average *E. coli* concentration during Summer

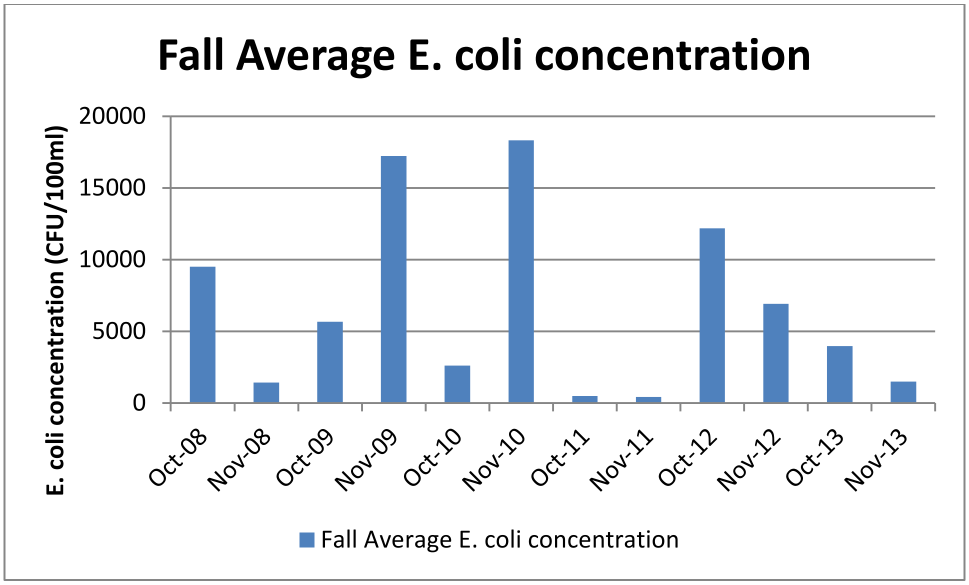

Figure 5. 45: Average *E. coli* concentration during Fall

5.3.4 Source Characterization

Six different sources of bacterial pollution were assumed in setting up SWAT model, namely cattle, horse, Canada goose, raccoon, white tailed deer and failing septic tanks. Then one source was added at a time and *E. coli* loading was evaluated. The loading resulting from septic tanks surpassed all other sources and appeared to be the most significant contributor towards *E. coli* loading in this watershed, whereas livestock activity is very limited and negligible forested area. Sources other than septic tanks according to decreasing contribution as predicted by model are Canada goose, cattle, raccoon, deer and horse. The average annual loading values from different sources (CFU/day) are presented in Table 5.4.

Table 5. 4: Average annual *E. coli* loading from different sources (CFU/day)

Year	Septic Tank	Canada Goose	Cattle	Raccoon	Deer	Horse
2001	16546531	3087	103	34	30	7
2002	73415049	3209	89	92	45	8
2003	11806180	4469	226	81	69	14
2004	74821858	3905	143	66	44	8
2005	8208657	589	5	6	2	0
2006	7814642	5242	184	51	51	11
2007	16370418	2575	96	33	23	5
2008	1460697	4223	112	33	28	6
2009	5125471	2757	81	20	18	4
2010	2981698	2950	99	45	30	6
2011	725400	7019	102	28	24	5
2012	9248415	2332	177	66	41	8
2013	1597011	7520	318	40	71	17
Average	17701694	3837	134	46	36	8

5.4.5 Sub-watershed Contribution

The contribution from each sub-watershed was compared to find out the areas contributing the highest bacterial concentrations and loadings. The concentration and loading values for each sub-watershed are presented in Appendix Table A-11. Figure 5.46 shows areas with high, medium and low *E. coli* concentration. Sub-watershed 2, 4, 8, 19, 21, 23, 26 and 30 were recognized as areas having the highest microbial concentration in reaches, while sub-watersheds 9, 11, 13, 14, 17, 18, 25, 28, 29 and 32 were having lower concentrations as compared to other areas. As septic tanks were detected as most significant source of *E. coli* loading, thus the number of septic tanks per sub-watershed and local hydrology at sub-watershed scale dictate this pattern.

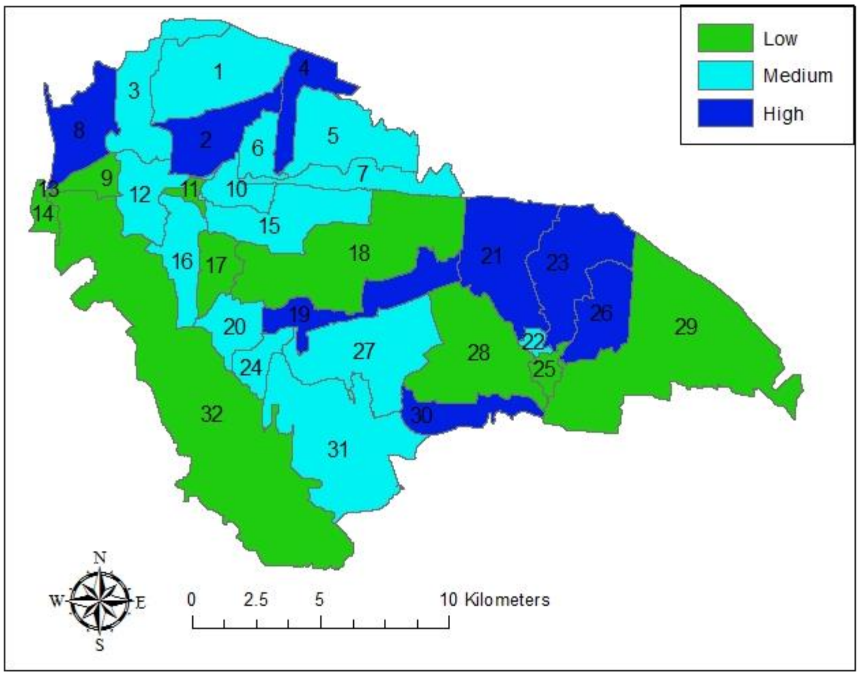

Figure 5. 46: *E. coli* concentration levels per sub-watershed

Further loading for each reach was also evaluated by multiplying *E. coli* concentration and flow in each stream. The Figure 5.47 shows the *E. coli* loading distribution in the different reaches of the Canard River watershed. It was noticed that the tributaries at the end were having the lowest loading values, but after the confluence loadings increased in secondary tributaries. The main stream carried the maximum loadings. This prediction is in-sync with general understanding that the amount of pollutant keeps on increasing in downstream as compared to upstream due to accumulation and input from new sources.

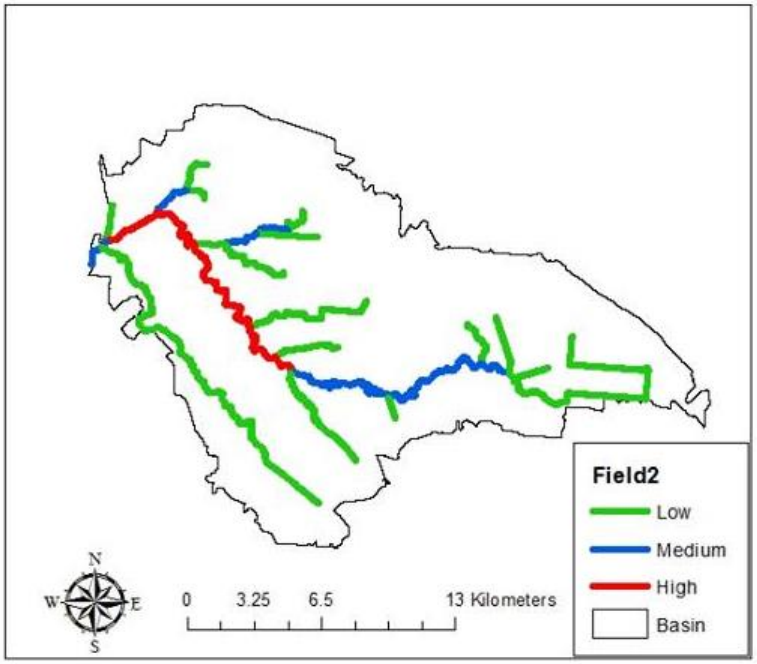

Figure 5. 47: *E. coli* loading in each reach

5.5 Summary

In this chapter the water budget analysis for Canard River watershed was performed to understand how the hydrological processes are influencing the water quantity and water quality issues. Then sediment and *E. coli* loading issues were addressed by performing sediment and *E. coli* analysis. These results helped in concluding the key points and putting forward suggestions to be considered while formulating and implementing water related policies for this watershed. Conclusions and recommendations are discussed in next chapter.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The hydrological analysis of the Canard River watershed was performed by using soil and water assessment tool (SWAT) to estimate the water budget and understand the sediment and E. coli fate and transport processes. The observed streamflow data from Lukerville monitoring station was used to calibrate and validate the model on daily basis. The Nash-Sutcliffe Efficiency (NSE) for calibration period (2001 – 2006) was 50 % while for validation period (2009 – 2012) was 56.4 %. Due to non-availability of observed sediment and *E. coli* data for simulated period, the model was not calibrated for water quality parameters.

The predicted streamflow on daily, monthly, seasonal and average annual basis demonstrated very high resemblance with monitored streamflow data. There were discrepancies for year 2003, 2006 and 2009 where the observed flow was less than the predicted flow. After review of both precipitation and streamflow, it was found that the error in monitored data or highly localized precipitation events demanding the need for more and better monitoring to better simulate the hydrological cycle. Seasonal flow analysis showed that the maximum streamflow occurred during winter season followed by spring, fall and summer. The model was able to capture the occurrence of peak in streamflow on daily time step but not the magnitude.

Water budget analysis showed that the major water loss occurred through evapotranspiration (65%) followed by surface runoff (25%) while tile flow (7%) and groundwater flow (3%) were lowest contributors towards water loss. Most evapotranspiration occurred during summer and least in winter. Maximum surface runoff occurred in winter while least in summer; whereas maximum baseflow occurred in spring and least in summer. The northern and south western sides of the watershed received higher precipitation while eastern and south eastern sides received lower precipitation. Thus the maximum surface runoff occurred in the northern and south western sides of watershed while the lowest surface runoff occurred in eastern and south eastern parts.

Based on limited observed sediment data, it was found out that the maximum sediment concentration occurred in winter season followed by spring, fall and summer. Similar pattern was observed in simulated sediment concentrations for different seasons. The higher and lower sediment loadings corresponded with the peakflows and baseflows. The simulated results showed that the average annual sediment loading values lied between 8 and 77 tonnes/day. The average sediment yield for Canard River watershed was found to be 2 tonnes/ha/day; while the average sediment yield for sub-watersheds lied between 0.18 and 6.3 tonnes/ha/day. The maximum soil erosion took place in northern part of the watershed due to higher precipitation and higher surface runoff whereas the southern part contributed least to sediment loading.

Model was not calibrated for *E. coli* loadings due to non-availability of monitored data. Thus only qualitative analysis was performed. The average daily concentration was found to vary upto six orders of magnitude with an average of 4424 CFU/100 ml. The analysis of *E. coli* over thirteen year period showed increase in loading. Seasonal analysis showed higher concentrations during winter and fall while concentrations were lower during summer and spring. The septic tanks were found to be most dominating source of *E. coli* followed by Canada goose, cattle, raccoon, deer and horse. The sub-watersheds in the northern and north-eastern were found to contribute significantly towards microbial loading.

6.2 Recommendations

Based on the research conducted for performing water quantity and quality analysis, the following recommendations have been suggested to improve modeling for future research studies.

1. The observed weather data for different stations was not available on continuous basis. The datagaps may need to be filled in using statistical procedures. The model performance could be tested using the newer data with relatively continuous and that is free of errors.
2. The streamflow data was not consistent with the observed precipitation in case of few events. This has resulted in significantly lower NSE values for daily time step simulations. The streamflow should be monitored carefully for better calibration and validation of models.
3. Data related to all soil parameters required for modeling should be available on single source for reducing the time and effort required for modeling.
4. Water quality data should be collected more frequently and for wide range of parameters for calibrating water quality parameters and ensuring the reliability of simulated results.
5. Septic tanks should be monitored and failure rates should be estimated for better modeling as they were found to impact pathogen loading significantly.

6. Livestock data should be collected on farm basis to incorporate their contribution towards pathogen loadings. Wildlife survey should be performed to enumerate the species present in this region.
7. SWAT model can be used in other agricultural dominated watersheds to perform water quality and quantity analysis. It can also be used to understand the impact of BMP’s in reducing the pollutant loadings.

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APPENDICES

Table A 1: Annual Observed vs Simulated flow comparison

Year	Precipitation	Simulated Average Annual	Observed Annual Average
2000	991.79	0.89	0.78
2001	799.53	1.67	1.73
2002	754.88	1.49	1.39
2003	906.75	2.16	1.14
2004	950.06	1.87	1.96
2005	748.69	1.57	1.63
2006	1081.16	2.61	2.02
2007	866.64	1.60	1.61
2008	1004.75	2.31	2.62
2009	892.34	2.14	1.73
2010	853.66	1.38	1.20
2011	1480.48	4.75	4.70
2012	712.04	0.93	0.64

Table A 2: Average Monthly and Seasonal Flow Comparison

Month	Average Precipitation	Observed Flow	Simulated Flow	Season	Observed Flow	Simulated Flow
Dec	77.53	2.80	2.58			
Jan	54.71	2.26	1.97	**Winter**	3	3
Feb	60.09	3.40	2.93			
Mar	67.31	3.55	4.59			
Apr	79.94	2.10	2.68	**Spring**	2.1	2.46
May	96.41	2.11	2.24			
Jun	74.31	0.83	0.57			
Jul	75.55	0.67	0.52	**Summer**	0.7	0.9
Aug	82.07	0.62	1.15			
Sep	79.48	0.68	1.34			
Oct	65.71	1.08	1.32	**Fall**	1.23	1.46
Nov	75.19	1.37	1.59			

Table A 3: Average Monthly Water Budget

Month	Precipitation (mm)	Surface Runoff (mm)	Water Yield (mm)	Evapotranspiration (mm)	Base Flow (mm)
Jan	99.41	25.92	31.47	5.52	5.55
Feb	94.52	39.51	42.9	10.72	3.39
Mar	87.19	36.05	52.42	27.61	16.37
Apr	92.04	19.58	31.93	53.02	12.35
May	86.86	17.09	27.18	76.52	10.09
Jun	78.95	11.95	15.13	103.03	3.18
Jul	84.81	9.24	11.81	121.06	2.57
Aug	81.97	6.99	7.62	78.07	0.63
Sep	86.31	10.36	11.63	44.56	1.27
Oct	70.36	10.07	13.72	34.07	3.65
Nov	72.54	13.57	20.84	19.21	7.27
Dec	98.14	26.47	35.66	12.65	9.19

Table A 4: Winter Water Budget Analysis from 2001-2012

Year	Month	Precipitation (mm)	Evapo-transpiration (mm)	Total Water Yield (mm)	Surface Runoff (mm)	Groundwater (mm)	Tile Flow (mm)
2001	1	18.44	0.02	3.89	6.45	0	0
	2	69.84	1.74	98.39	98.79	0.84	0
	3	27.31	16.33	19.65	10.1	4.6	6.43
	12	51.49	12.4	52.68	13.87	6.94	29.81
2002	1	82.67	2.71	30.3	35.01	3.58	9.96
	2	34.42	7.66	45.62	9.51	6.44	21.18
	3	52.51	15.21	30.93	23.9	2.72	9.27
	12	74.41	14.99	37.68	43.32	0.23	0.51
2003	1	42.39	0.01	8.38	2.06	0.01	0
	2	61.52	0.03	13.06	13.03	0.01	0
	3	62.03	9.62	118.71	99.97	6.83	18.98
	12	75.9	17.06	47.52	27.42	6.39	19.57
2004	1	44.65	0.28	14.43	1.7	3.47	11.26
	2	20.95	2.65	35.64	34.91	0.96	1.07
	3	91.02	14.85	60.02	24.91	9.37	35.69
	12	71.59	15.33	45.63	26.05	6.3	21.74
2005	1	101.56	0.1	66.57	60.12	3.34	0.33
	2	69.36	0.55	41.33	41.15	3.98	0
	3	25	9.93	61.36	32.99	7.02	28.03
	12	90.43	16.53	30.83	33.87	0.14	0.1
2006	1	83.18	1.68	79.79	32.33	13.99	43.74
	2	62.22	4.67	45.46	30.68	5.07	13.48
	3	60.31	18.07	45.16	18.82	7.24	26.09
	12	76.24	16.05	62.55	23.91	7.71	30.98
2007	1	28.91	2.68	11.6	4.22	2.24	6.48
	2	19.27	0	1.89	3.72	0.01	0
	3	82.04	14.16	81.47	61.67	6.07	18.5
	12	89.07	16.43	26.06	25.51	0.08	0.22
2008	1	64.28	0.63	75.05	57.98	6.47	18.67
	2	119.67	0.26	56.95	54.85	0.31	0.02

	3	98.58	4.3	113.33	108.23	10.02	9.31
	12	104.82	21.86	62.16	64.71	0.4	0.5
2009	1	45.59	0.03	3.79	0	0.33	0
	2	75.92	1.15	101.45	103.88	2.74	0
	3	119.18	17.97	115.91	76.65	11.81	36.74
	12	72.77	16.38	34.27	33.4	0.85	1.16
2010	1	24.11	0.64	16.8	16.64	0.58	0
	2	47.49	0.18	7.18	8.84	0.21	0
	3	47.4	17.26	55.3	25.26	9.86	28.1
	12	64.86	11.32	10.29	11.58	0.49	2.37
2011	1	78.87	0.05	25.64	18.94	0.02	0
	2	107.6	0.14	47.86	48.89	0.56	0
	3	104.26	7.98	211.69	171.3	16.71	39.29
	12	84.45	18.66	81.88	24.34	9.05	40.35
2012	1	55.27	2.51	39.22	31.36	3.02	7.65
	2	41.83	7.07	28.88	14.33	4.89	16.24
	3	57.83	28.88	36.02	14.69	5.79	19.68
	12	52.59	9.06	12.52	5.47	2.92	6.87
	Average	65.34	8.29	49.02	36.07	4.22	12.09

Table A 5: Spring Water Budget Analysis from 2001 - 2012

Year	Month	Precipitation (mm)	Evapo-transpiration (mm)	Total Water Yield (mm)	Surface Runoff (mm)	Groundwater (mm)	Tile Flow (mm)
2001	4	60.14	35.44	15.44	7.8	3.35	7.41
	5	75.68	83.73	3.49	2.86	0.31	0.53
2002	4	108.24	29.41	70.17	36.36	8.98	30.9
	5	89.96	54.69	43.03	25.69	6.24	17.55
2003	4	68.02	29.45	29.2	17.25	5.91	16.15
	5	131.5	55.76	52.41	33.39	6.55	18.66
2004	4	36.51	31.91	19.18	5.93	3.16	11.69
	5	164.65	77.55	78.65	47.15	10.23	31.03
2005	4	86.59	33.96	43.53	26.28	5.74	17.49
	5	31.99	52.6	5.86	3.4	1.27	1.75
2006	4	56.4	38.03	22.72	11.4	4.44	11.01
	5	110.92	79.32	33.45	18.95	4.09	14.39
2007	4	99.7	26.59	50.85	34.67	6.35	20.29
	5	42.36	68.29	21.16	6.66	4.35	9.05
2008	4	34.91	34.13	44.22	1.87	7.59	37.56
	5	53.91	55.38	7.38	6.05	0.39	1.19
2009	4	121.67	33.26	61.85	35.87	9.99	30.48
	5	52.64	62.89	25.78	12.97	3.45	7.31
2010	4	80.71	40.49	36.31	25.96	3.85	9.86
	5	119.12	76.1	55.47	30.12	7.85	24.69
2011	4	135.13	27.66	86.34	39.13	15.06	46.99
	5	175.36	58.78	105.18	67.72	13.27	38.93
2012	4	30.22	36.94	4.64	5.33	0.18	0.22
	5	83.81	98.37	10.82	7.53	0.15	0.79
	Average	85.42	50.86	38.63	21.26	5.53	16.91

Table A 6: Summer Water Budget Analysis from 2001 - 2012

Year	Month	Precipitation (mm)	Evapo-transpiration (mm)	Total Water Yield (mm)	Surface Runoff (mm)	Groundwater (mm)	Tile Flow (mm)
2001	6	36.35	91.06	2.17	0.83	0.23	1.23
	7	30.17	57.43	0.27	0.24	0.01	0
	8	45.54	37.11	3.53	3.42	0.01	0
	9	118.29	45.77	28.27	28.1	0.01	0
2002	6	35.89	92.1	1.42	0.5	0.29	0.21
	7	56.83	61.93	2.77	3.01	0.02	0
	8	20.44	37.73	1.05	0.61	0.01	0
	9	37.11	26.57	3.32	3.56	0.01	0
2003	6	88.99	103.9	33.91	22.87	1.77	5.85
	7	51.01	86.9	1.42	1.32	0.06	0.01
	8	135.23	77.03	29.06	32.43	0.13	0.29
	9	72.8	43.56	20.17	16.14	0.08	0.23
2004	6	78.27	117.02	5.46	3.4	0.89	1.84
	7	75.12	72.56	5.2	6.54	0.05	0
	8	131.62	75.65	42.47	42.91	0.29	0.6
	9	26.52	38.88	6.56	3.61	0.05	0.04
2005	6	18.61	72.11	0.07	0.01	0.04	0
	7	85.24	73.79	7.8	8.05	0.01	0
	8	53.14	45.75	7.85	7.91	0.01	0
	9	63.79	41.61	9.92	9.4	0.01	0
2006	6	92.23	119.23	10.9	10.52	0.31	0.1
	7	102.11	90.96	12.54	13.44	0.02	0.03
	8	83.88	60.24	19.42	19.65	0.01	0
	9	139.72	57.65	47.39	48.86	0.06	0.55
2007	6	46.04	92.78	1.54	1.49	0.06	0.01
	7	40.76	53.99	4.72	4.66	0.02	0
	8	189.4	78.51	62.96	61.85	0.29	0.89
	9	45.8	41.81	12.55	12.2	0.06	0.02
2008	6	142.48	149.81	10.95	10.7	0.3	1.54
	7	83.5	111.37	9.84	6.54	0.54	1.75
	8	16.19	33.82	0.23	0.17	0.02	0
	9	104.4	40.45	31.43	31.29	0.01	0
2009	6	103.74	111.73	12.33	12.32	0.12	0.1
	7	39.49	75.18	1.05	0.71	0.01	0
	8	92.47	57.75	20.23	22.35	0.01	0
	9	35.36	36.53	5.85	3.68	0.01	0
2010	6	82.66	123.45	5.71	4.92	0.38	0.69
	7	121.55	81.96	37.54	38.03	0.01	0.28

	8	9.39	35.4	1.14	0.14	0.01	0
	9	62.54	36.91	8.8	9.94	0.01	0
2011	6	72.15	101.95	20.41	14.44	2.19	3.05
	7	141.32	114.88	27.78	30.7	0.06	0.19
	8	108.77	76.78	34.97	30.7	0.1	0.85
	9	185.68	62.68	73.1	59.09	3.49	14.56
2012	6	35.98	82.7	0.52	0.3	0.01	0.1
	7	80.28	68.71	15.73	16.6	0.01	0
	8	83.7	55.55	19.44	18.58	0.01	0
	9	48.05	40.7	2.26	1.91	0	0
	Average	76.05	70.67	15.08	14.18	0.25	0.73

Table A 7: Fall Water Budget Analysis from 2001 - 2012

Year	Month	Precipitation (mm)	Evapo-transpiration (mm)	Total Water Yield (mm)	Surface Runoff (mm)	Groundwater (mm)	Tile Flow (mm)
2001	10	150.69	44.27	60.38	46.55	3.77	13.45
	11	67.95	18.51	24.91	21.36	3.52	11.93
2002	10	32.17	18.27	3.1	2.75	0.01	0
	11	74.71	18.83	14.24	13.85	0.01	0.12
2003	10	61.2	28.41	20.71	20	0.01	0.4
	11	78.04	21.62	32.54	16.04	5.56	17.69
2004	10	50	23.3	6.02	6.3	0.02	0.02
	11	95.43	23.44	33.55	24.43	3.94	11.87
2005	10	7.6	17.9	0.31	0.04	0.01	0
	11	87.73	20.51	22.7	23.39	0.01	0.15
2006	10	118.17	37.18	67.93	35.5	7.03	28.96
	11	76.53	20.12	40.63	25.69	5.09	21.95
2007	10	56.88	31.44	10.03	9.83	0.01	0.05
	11	49.69	12.38	14.2	13.66	0.31	0.75
2008	10	31.49	20.76	2.6	2.45	0.01	0
	11	99.31	24.06	23.75	22.47	0.98	1.63
2009	10	77.7	30.25	14.67	14.08	0.02	0.25
	11	16.91	9.46	0.9	0.29	0.21	0.52
2010	10	45.16	24.38	8	6.61	0.01	0
	11	86.51	18.41	20.28	21.19	0.93	1.73
2011	10	97.07	36.69	62.58	37.42	6.04	23.57
	11	186.64	34.32	110.52	101.3	7.02	26.69
2012	10	58.48	24.67	2.88	3.08	0	0.01
	11	15.52	7.39	2.7	1.73	0.27	0.48
	Average	71.73	23.61	25.01	19.58	1.87	6.76

Table A 8: Sub-watershed wise Water Budget Analysis

Sub-watershed	AREA (km^2)	PRECIP (mm)	ET (mm)	WYLD (mm)	SURQ (mm)	GW (mm)
1	13.97	972.61	496.02	430.34	333.82	30.40
2	7.74	972.61	499.01	434.64	340.22	20.09
3	9.00	972.61	465.97	482.81	331.50	13.81
4	5.19	972.61	461.16	515.86	318.10	0.00
5	11.06	972.61	475.62	474.85	300.29	23.57
6	3.26	972.61	494.29	467.56	312.45	0.00
7	6.32	972.61	464.20	512.83	327.86	0.00
8	7.89	966.85	460.00	449.96	339.31	32.29
9	2.54	879.88	455.08	426.87	328.54	17.98
10	3.36	972.61	461.93	432.49	349.43	50.02
11	0.94	966.85	542.48	386.63	282.88	14.39
12	6.32	953.59	471.67	435.21	310.78	41.51
13	0.09	862.71	406.54	409.38	323.28	85.71
14	1.58	892.31	436.97	393.43	329.62	63.68
15	10.31	972.61	463.60	484.40	332.87	17.98
16	6.20	966.85	486.23	419.85	327.03	25.87
17	4.04	966.85	467.84	398.85	343.49	55.30
18	23.64	972.61	472.25	461.19	300.86	39.18
19	8.23	857.91	450.31	365.00	265.10	19.07
20	4.52	966.85	500.34	399.10	304.59	37.26
21	13.72	857.91	451.42	412.67	265.09	0.00
22	0.89	857.91	492.14	318.30	247.76	8.33
23	12.41	857.91	478.58	363.90	275.73	3.98
24	3.01	966.85	534.73	386.16	278.76	18.85
25	1.65	857.91	507.53	292.23	222.59	18.27
26	7.09	857.91	451.38	412.75	254.58	0.00
27	15.05	857.91	482.66	333.38	241.08	8.85
28	15.66	857.91	463.74	334.55	260.59	24.93
29	33.68	857.91	457.16	384.52	240.16	13.16
30	5.34	857.91	454.27	350.22	272.77	16.00
31	21.91	857.91	453.98	331.09	289.36	15.79
32	53.13	966.46	466.95	503.90	304.61	0.00

Table A 9: Sub-watershed wise Sediment Yield

Sub-watershed	Sediment Yield (t/ha)
1	1.87
2	1.81
3	1.97
4	3.58
5	3.35
6	3.18
7	6.30
8	2.28
9	1.70
10	2.20
11	0.48
12	1.72
13	2.98
14	2.12
15	3.29
16	1.77
17	1.53
18	2.00
19	1.97
20	1.49
21	1.83
22	1.74
23	1.45
24	0.64
25	0.18
26	2.45
27	1.13
28	1.34
29	0.63
30	1.88
31	2.32
32	0.90

Table A 10: Seasonal *E. coli* Average Concentration (CFU/100ml)

Date	Winter	Date	Spring	Date	Summer	Date	Fall
Jan-08	1227	Apr-08	604	Jun-08	533	Oct-08	9505
Feb-08	910	May-08	848	Jul-08	1057	Nov-08	1429
Mar-08	347	Apr-09	240	Aug-08	2519	Oct-09	5663
Dec-08	675	May-09	486	Sep-08	2272	Nov-09	17226
Jan-09	3672	Apr-10	651	Jun-09	642	Oct-10	2604
Feb-09	732	May-10	248	Jul-09	1539	Nov-10	18324
Mar-09	562	Apr-11	244	Aug-09	35848	Oct-11	480
Dec-09	1594	May-11	200	Sep-09	29044	Nov-11	413
Jan-10	2392	Apr-12	623	Jun-10	544	Oct-12	12192
Feb-10	3573	May-12	814	Jul-10	703	Nov-12	6904
Mar-10	485	Apr-13	529	Aug-10	4493	Oct-13	3977
Dec-10	3206	May-13	522	Sep-10	7026	Nov-13	1485
Jan-11	4100			Jun-11	353		
Feb-11	4131			Jul-11	439		
Mar-11	353			Aug-11	705		
Dec-11	198			Sep-11	511		
Jan-12	241			Jun-12	50016		
Feb-12	300			Jul-12	2033		
Mar-12	377			Aug-12	10971		
Dec-12	2370			Sep-12	3706		
Jan-13	2181			Jun-13	403		
Feb-13	1038			Jul-13	275		
Mar-13	546			Aug-13	653		
Dec-13	2135			Sep-13	1340		

Table A 11: Average annual *E. coli* concentration and loading for each sub-watershed

Sub-watershed	*E. coli* concentration (CFU/100ml)	*E. coli* Loading (CFU/day)	Sub-watershed	*E. coli* concentration (CFU/100ml)	*E. coli* Loading (CFU/day)
1	47924.55	268355.4	17	24214.03	2822898
2	121598.2	271046	18	16228.32	257166.4
3	51270.62	781900.8	19	273092	217123.1
4	392356	226752.4	20	53335.87	2418071
5	42008.79	278228.4	21	290775.6	167736.1
6	76945.31	746226.2	22	64327.39	1057739
7	149290.9	188444.4	23	275156.3	194718.1
8	132153.3	257785	24	69325.51	2056058
9	14903.17	5510573	25	82502.74	647357.1
10	52747.2	1163092	26	384153.9	175909.8
11	21325.08	1639334	27	60992.59	1638333
12	33723.62	4631534	28	52192.7	1325064
13	10247.56	5997013	29	33798.42	202847.5
14	4851.662	6427509	30	561486.3	232899.1
15	65909.48	242246.8	31	109536.9	201299.5
16	37076.83	2949864	32	14834.24	193307.5

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